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PH.D THESIS

QUALITY OF SERVICE THROUGH CROSS-LAYER TECHNIQUES FOR THE FUTURE INTERNET

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1. Introduction

It is a fact that nowadays the Internet is an important part of our lives, bringing people together and facilitating the access to valuable information. In order to meet the end-users demands, new services are being made available each day. It is important to mention that the most popular ones are dedicated to sending/ receiving real-time information (i.e. voice over IP, video over IP, IP television). These types of services have stringent QoS (Quality of Service) requirements and if they are not being met by the underlying network, the user experience will be degraded significantly.

1.1 Existing QoS Solutions

Integrated Services (IntServ): is considered to be the first attempt of the Internet Engineering Task Force (IETF) to insert QoS mechanisms into the network's architecture. The main characteristic of the system is that it is trying to guarantee a per-flow level of QoS, using the RSVP (Resource Reservation Protocol).The required QoS level is assured for every micro traffic flow that is crossing the network if employing the IntServ protocol. There are some disadvantages related with the scalability of the mechanism, due to the fact that a per-flow signalling is necessary to be implemented in the routers.

Differentiated Services (DiffServ): Admitting that IntServ has major issues in what concerns the scalability of the mechanism, the IETF developed another architecture called Differentiated Services (DiffServ). This new approach was trying to overcome the scalability issues of its predecessor. The main characteristic is the insertion of the service differentiation concept that is defining a number of traffic classes. One limitation that is characterising the DiffServ approach is the fact that the mechanism does not have a real-time overall perspective of the network.

1.2 Overview of the Cross-Layer Paradigm

Nowadays, when the real-time services are becoming more and more popular, the classical approach for QoS guaranteeing is not suitable anymore. This is due to the fact that the traffic parameters need to be kept in a stringent domain in order for the user to receive a specific level of Quality of Experience (QoE). The cross-layer paradigm was proposed to be a solution for this challenging problem, bringing the possibility for protocols to exchange management information with others, so that a global image of the network's performance to be created in real-time and optimal decisions to be taken. Thus, communication protocols from upper layers are able to adapt their behaviour according to the variation of the traffic parameters from lower ones.

1.3 Overview of the In-Network Management Framework

The concept of In-Network Management (INM) was developed within the FP7-4WARD project, to be implemented for the Future Internet. It is a paradigm that enhances management operations to be highly distributed between all the nodes of a communication domain. The main objective is to design the management functions to be located as close as possible to the managed services. As a target approach, they would be co-designed with the existing services. One of the main challenges is to identify the suitable INM paradigm that can be used for embedding management capabilities into the network. The benefit of the resulting distributed architecture is the inherent support for self-management features. In line with a clean slate approach, the INM framework proposes a new set of fundamental principles and constructs new methods on how to design and operate concrete networks according to the INM paradigm.

2. Contributions to QoS through Cross-Layer Techniques for the Future Internet

Classification and Evaluation of Cross-Layer QoS Mechanisms

The work presented in chapter 2 was focused on investigating a number of five types of cross-layer architectures: bottom-up, top-down, back and forth, merging of adjacent layers and vertical calibration. Moreover, a set of techniques that can be used to implement the previously mentioned signalling architectures were also described: direct communication between different layers, using a shared database, renouncing to the concept of protocol layers by using a new abstraction and activating a specialised optimization module. The second part of this chapter is dedicated for studying existing cross-layer implementation and classifying the exchanged signalling according to a precise set of characteristics. Thus, considering the type of information exchanged, there can be: status information or control information while the delivery method with respect to the used path can be: in-band or out-of-band. If considering the area where the signalling information is travelling, two categories can be outlined: cross-layer information exchanged inside or outside the node. If considering the adaptation process, a certain implementations can be: synchronous or asynchronous while being located inside (i.e. inherent) or outside the communication process.

Publications: [Rus08b], [Rus09a]

Design and Preliminary Implementation of a Clean-Slate Architecture for Cross-Layer QoS

The concept of inherent management presented in this thesis was enhanced with QoS capabilities by implementing a dedicated module that uses bottom-up and top-down cross-layering techniques for exchanging status and control information, transmitted both in-band and out-of-band. The proposed Cross-Layer QoS (CLQ) module runs on top of the MAC sub-layer and uses a customized set of XML messages for exchanging data with other entities included in the future Internet (i.e. Generic Path, NetInf). Moreover, for completing the overall description of the CLQ module, the complete SDL diagram describing the states through which it can pass, was also designed. The actual implementation of the Cross-Layer QoS module was made on every node of the managed infrastructure, on top of the Linux operating system, inside the Java programming language and over the OSGi framework.

Publications: [Rus09b], [Nun09], [Nun10], [Gon10], [Rus10a], [Car10]

Proposed Methodologies for Measuring QoS Parameters

The original CLQ implementations included in this chapter are based on theoretical concepts of inherent management which were recently introduced within FP7-4WARD project. This contribution includes a set of measuring techniques proposed to monitor the following set of quality of service parameters: Round-Trip Time (RTT), One-Way Delay (OWD), Available Transfer Rate (ATR) and Bit Error Rate (BER). The first two QoS parameters were determined using active measuring techniques by sending customized probes on the monitored communication link. When measuring the available transfer rate of a particular channel, passive techniques were employed. In order to monitor the reliability of a communication link, the BER parameter was estimated using specific mathematical models that are describing the BPSK, QPSK and N-QAM modulations. The underlying technologies for which the BER was analysed are the following: 802.11 a/b/g and xDSL.

Publications: [Rus09b]

Implementation and Evaluation of Cross-Layer QoS for Congestion Control

If in a congested network no additional resources can be added, Cross-Layer QoS mechanisms can be used to trigger cooperative coding techniques (i.e. Network Coding) that are an alternative solution to the QoS aware routing. Network Coding (NC) implementations are using available resources from other segments of the communication topology to accommodate the data traffic. For validating this contribution, a set of tests were employed, where a preliminary implementation of the NC mechanisms was made at Application Layer. The butterfly topology was used as an underlying infrastructure while on each node the Linux operating system was running. The employed set of experiments, proved that the congestion can be faced (without eliminating it), so that the amount of lost packets to drop down from 20% to less than 1%. After demonstrating and validating the feasibility of the current idea, in the first set of experiments, the second research study was focused on moving the NC implementation to the Network Layer. The overall conclusion of this contribution states that combining Cross-Layer QoS mechanism with Network Coding processing, results an adaptive NC infrastructure that can react to various changes of the network.

Publications: [Rus10a], [Rus10b], [Pol09a], [Vin10], [Kis11], [Cor11]

Implementation and Evaluation of CLQ for QoS-Aware Routing

The Cross-Layer QoS proposed within this contribution is being utilised for optimising the forwarding mechanisms dedicated to dynamically route the data packets inside the network. This action is being accomplished by imposing a real-time updated composite metric, which globally reflects the actual network state. The QoS parameters considered when calculating the composite metric are the following: ATR, OWD and BER, measured for each link connecting various combinations of nodes. The actual implementation was made on a set of virtual routers, created using the Vyatta software product, running on top of a Debian Linux distribution. It was demonstrated that routing protocols can be enhanced to avoid congestion, otherwise transparent for the classical approaches. In case that multipath routing is needed to be activated, CLQ can be used to find the optimal set of paths to forward the data traffic. For choosing the best available solution, a set of statistical operations that are considering the available transfer rate parameter, are being run.

Publications: [Rus10c], [Rus10d], [Boa10]

Implementation and Evaluation of CLQ Module for MPLS Routers

Historically speaking, the current contribution was the first one performed in this research work. Its main purpose was to demonstrate the feasibility of the idea that states that it is possible to automate traffic engineering tasks. The MPLS technology was chosen due to the fact that it is already QoS aware, containing mechanisms dedicated to perform related tasks. Thus, the parameters obtained from the lower layers (i.e. ATR, OWD and BER) are being grouped into a Composite Metric that is being published into the MPLS aware domain through the label distribution mechanisms. The simulations executed inside the OMNET++ environment, demonstrated that a 20% improvement of the communications quality can be achieved if implementing the proposed mechanism. The performance of the whole system can be further improved if adding a management system dedicated for performing various statistical operations considering the dynamicity of the whole domain. For adding this improvement, the needed performance parameters extracted above the MAC sub-layer will be provided by the CLQ module.

Publications: [Rus10b], [Bar11]

Enhancing Dijkstra's Algorithm with Cross-Layer QoS

The performance of the Dijkstra's algorithm can be improved with the help of the cross-layer QoS module. The algorithm periodically computes the spanning-tree of the communications topology, considering the updated traffic parameters (i.e. ATR, OWD and BER). This enhancement is needed due to the fact that the performance indicators of the communication channels are constantly changing in time. However, the actual modifications made to the classical version of the algorithm are more consistent than a simple replacement of the used metric with a global indicator of the overall status (i.e. composite metric). Thus, new parameters such as OWD and BER are being taken into account when computing the cost of a communications channel, while the ATR parameter is no longer considered to be equal with the actual capacity of a link. Moreover, the ATR indicator for a path is the minimum available transfer rate of the links composing it. Finally, the global value for the BER parameter is also being computed. For validating the mathematical expression used to calculate the composite metric, an implementation in OMNET++ was performed and a set of several tests was executed. Thus, it was further demonstrated that the end-to-end delay obtained when using the modified Dijkstra's algorithm can be significantly lower if an alternative path with superior performance is available in the communications topology. Note that the classical version of the algorithm is not capable of detecting in real-time variations of the QoS parameters. It can only sense significant link state changes that are appearing in the communication topology (i.e. existing links are becoming unavailable, new ones are being activated or the underlying technology is being changed).

Publications: [Rus10b], [Rus10c]

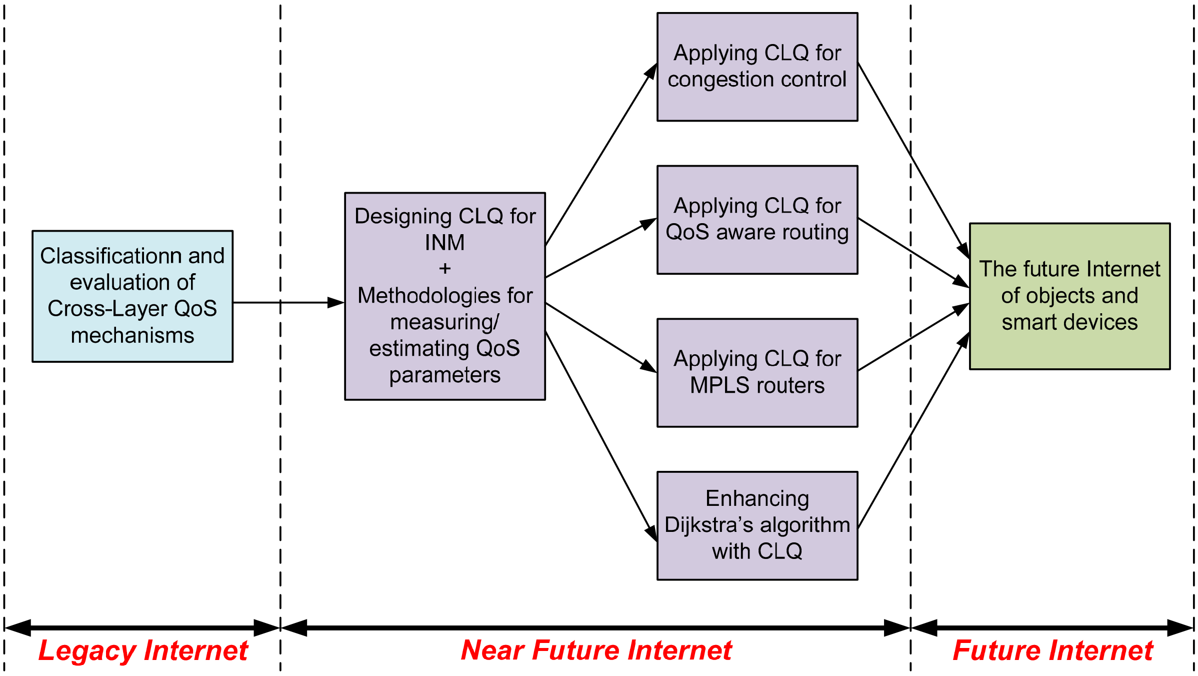
The Future Internet of Objects and Smart Devices

This contribution refers to the integration of the QoS information and routing mechanisms into a single entity called Intelligent Information Object – IIO (i.e. containers dedicated for carrying user data through the network). One of the main characteristic of any IIO is the self-routing property that can be implemented into a network composed of Smart Devices. Moreover, new concepts bringing radical changes in the networking paradigm are being proposed to be implemented in the future Internet. Thus, the network will be an object oriented one rather than a network focused on connecting communication devices. Based on the contributions presented until now, a new idea that states that the CLQ mechanism is the one that can facilitate the collaboration between IIOs and Smart Devices was also crystallised.

Publications: [Rot09], [Nun09], [Gon10]

3. Final Remarks

The scope of the current thesis was to evaluate the feasibility of adding cross-layer techniques to enhance the quality of the services available in the networking world. The work started in the first phase with an overview of the existing cross-layer techniques that can be found in the specialised literature. In the second phase of this thesis, after designing a mechanism capable of implementing cross-layer signalling, a couple of applications were enhanced with this new concept, and a series of tests were employed to verify their performance. Because these applications are using the current Internet infrastructure, a real deployment of this paradigm can be made in the near future Internet. The third phase is being focused on illustrating more radical changes that are proposing new paradigms to be implemented in the data communication network of the future. Thus, the network will be more information-centric than before, supporting concepts such as Intelligent Information/ Resource Object and Smart Devices.



Structure of the current thesis

4. Awards

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- **First 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 2007.

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