

Annual Report 2006

Q2S

Centre for Quantifiable Quality of Service in Communication Systems



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In October 2006, Q2S together with 12 other Norwegian CoE's underwent a midway evaluation organized by the Norwegian Research Council. The preparation of the report to the research Council was a major effort by Q2S in the first half of 2006. A revised research plan for the second five year period of functioning of the centre was compiled through a thorough internal process with seminars and meetings as a basis for the self-evaluation report¹. In addition to the internal seminars and meetings, we engaged four well known international researchers to participate in an Ad Hoc Advisory Group to aid in setting the goal, direction and focus of both the ongoing and future research at the centre. The work was organized as a two-day seminar in Trondheim with the senior researchers of Q2S. We feel that this process has prepared us well for the continued high quality research to be performed in the second five year period of existence for the CoE.

We are proud of our research achievements made in the first three and a half years of our existence, and were very happy to read the positive evaluation by the scientific experts appointed by the Research Council. The main evaluation committee, however, in their total assessment voiced some critical comments. A stronger integration of the research areas was recommended, and increased international visibility through more international collaborative projects and more international visits was advised. However, since the time the evaluation documentation was prepared and at the time of writing this report, the situation has already changed markedly for the better. We are now in the fortunate position that the international visibility and

our attractiveness as a CoE for international experts to visit has increased significantly, and the number of applications for positions at the centre at all levels has increased to a more satisfactory level. We are nevertheless constantly working to improve on the areas of activity where weaknesses were identified², and we are confident that there is a significant potential for even better achievements to be made.



Change of leadership. Peder J. Emstad and Svein J. Knapskog.

Encouraged by the Board of the centre we have decided to establish a permanent Advisory Board for the next five years. Five internationally well-known experts have been invited to participate, and all have accepted the invitation. Advisory Board meetings will be called as needed, at least once a year. Meetings will be organized as strategic seminars with participation from all researchers at Q2S.

In the second half of 2006, preparations have been done for arranging NGI 2007 which is the main conference for the EuroFGI (former EuroNGI) Network of Excellence. The conference will take place in May 2007 with an expected participation of approximately 100 researchers from all over the world.

There has been a change in the leadership of Q2S. Professor Svein J. Knapskog took over as centre director from October 1st, as professor Peder J. Emstad stepped back due to age. Professor Peder J. Emstad has successfully worked for the centre since the founding invitation by the Research Council in 2001, and headed the centre in the build-up period from its start in 2002. Professor Knapskog is one of the six founding senior researchers of the centre since its establishment, and is determined to forcefully keep up the momentum of focused research relevant for quantifiable quality of service in communication systems, based on the foundation laid over the first three and a half years of activity and recently expressed in the revised research plan for the centre¹.

Professor Emstad is enjoying a research leave in the academic year 2006/2007, while still keeping up his supervising activities for the PhDs at Q2S in his area of research, as well as being active in the organizing of the NGI 2007 conference. At the time of writing, professor Emstad is visiting University of Stuttgart, Institute of Communication Networks and Computer Engineering.



Pro-Rector of Research and Innovation, NTNU, Astrid Lægrind and Chairman of the Board, Nils Holme

- 1 Midway Evaluation of the Centre of Excellence Q2S, project no. 1460051420, April 2006.
- 2 Midway Evaluation of the Norwegian Centres of Excellence, The Research Council of Norway, November 10 2006

The scientific mission of the centre is basic research on Quality of Service (QoS) issues in heterogeneous, multilayered networks based on packet switching technology. Quality of Service relates to the user experience and satisfaction of traditional tele-, multimedia-, web-, info-, message- as well as location- and content-aware services. The centre concentrates on issues of multimedia signal processing, dependability, traffic and security as applied to multiparty communication. QoS is a multifaceted research area. The research draws on several technological disciplines traditionally treated one by one in isolation from each other. Q2S research addresses the totality. The associated technological disciplines will all have to be pursued in depth within the framework of the totality. The research approach is to define cross-disciplinary projects contributing to the common goal of developing Quantifiable Quality of Service. This is a self-evident part of future user-centric Service Level Agreements (SLAs). Our research areas are illustrated in figure 1, where the centre of the

picture illustrates how the six disciplinary areas that form the scientific foundation of the centre contribute to the cross-disciplinary emphasis on developing the quantifiable aspects of QoS.

Addressing QoS in a cross disciplinary manner is important, since it is the totality of the contributions from the disciplinary aspects which are decisive for the perception of the timeliness, performance and trustworthiness determining the users experience of the service. The strength of Q2S is its ability to define the research projects in a cross-disciplinary and quantifiable manner. Furthermore, there are complicated and intrinsic relations between the various facets of QoS and the disciplinary issues. For instance:

- introduction of security mechanisms has severe impact on the timeliness of a system and may reduce the overall reliability,



The Q2S Centre

- A Norwegian Centre of Excellence (CoE) initiated by the Research Council of Norway
- Started January 1st, 2003
- Financed for 5 years by
 - Research Council of Norway
 - NTNU
 - UNINETT
- Supported by Telenor
- Presently a scientific staff of 30 and 2 administrative/technical personnel

Research Areas

- Audio over IP* Networks
- Multimedia over IP Networks
- Intradomain Networks
- Interdomain and Overlay Networks
- Trustworthy Multiparty Interactions in Dynamic Networking Environments

The Centre has now 13 internally defined projects in these areas

* IP stands for Internet Protocol

International Cooperation

- Member of EuroFGI, a Network of Excellence under European Commission's 6th Framework Programme
- Participates in COST action COST 290
- Participates through UNINETT in the EU project LOBSTER

- traffic handling during failures is a combined research issue in both traffic and dependability disciplines,
- perceived QoS highly depends on how the different service elements are prioritized when network elements come close to overload.

Providing QoS is pivotal for dimensioning a communication system, both in terms of resources put into the network and operation and management, and its overall usefulness and economy. Hence, being able to deal with QoS in a quantitative manner, improves our ability to balance advantages and risks vs. cost.

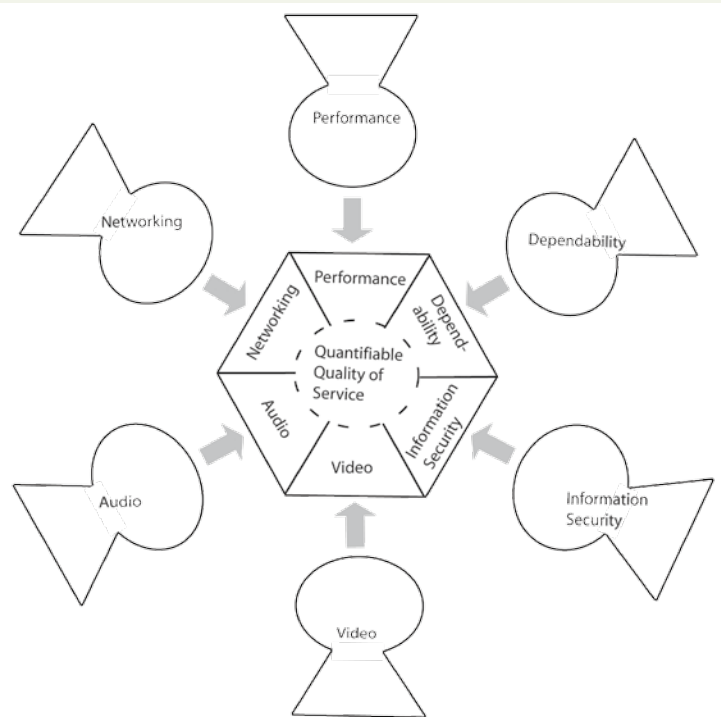


Figure 1. Quantifiable Quality of Services as a result of co-operative cross-disciplinary projects.

This is of utmost importance in order to be able to build the future ICT infrastructures. For this reason the centre addresses quantification more consequently and in a manner which goes beyond the state of the art, and beyond what has been addressed in relevant research programs so far.

As is evident from the above, our scope is broad. For the coming period, Q2S will focus on answering three long term interrelated research questions which will have a major impact on the design and operation of future generations of systems:

1. How may (real time) interactive media be handled in the network to meet service requirements in an efficient manner and minimize the effect of network resource limitations and failures?
2. How may resources be managed, paths found and altered in a manner that ensures a predictable QoS to the users, when users and (some) network elements are mobile, operation of network segments is uncoordinated, there are deliberate attacks against network elements and user's services, random failures occur, and the offered traffic is variable and rather unpredictable?

3. How may the QoS be assessed both in terms of user perception and objective quality measures, in a network context as outlined above? An important constraint in this work is that the measurement system/additions shall not incur a significant cost relative to the cost of service provision.

This research focus is addressed in the revised research plan for the centre.¹ The research plan gives a more detailed description of the background, research objectives and approach than what is outlined above. The research plan is aimed at enforcing the cross disciplinary aspect of answering the three major research questions. The chosen research areas map the research questions. The research problems addressed within each area is exemplified by the arrows in figure 2. The broad-spectered measures considered in Q2S research are shown on the user network interface. The specific issues dealt with in the plan are regarded as highly relevant for future application and commercialization of QoS oriented services.

¹ Plan for second five-year period ; Part D of the documentation for the *Midway Evaluation of the Centres of Excellence*. Q2S, April 2006.

Quantitative Quality of Multimedia Services

The following is one example of how quantitative quality of service may materialize in a multimedia setting, as shown in figure. 3.

For IP networks, the deterioration in perceived quality is typically due to packet loss. The other major source of distortion and degradation of perceptual quality in multimedia communication is because of the inevitable coding and compression of media sources. In particular, for block-based video compression schemes such as the ISO/IEC and ITU standards (e.g. MPEG-1/2/4, H-261/3/4), the main forms of distortions include block impairment effects, blurring, ringing and several other effects with negative influence on the images.

No-Reference (NR) metrics which have been proposed, in general at quantifying these distortions but the emphasis of research on NR metrics has been predominantly on quantifying the effects of block impairment artifacts. This is because block impairment artifacts tend to be perceptually the most significant of all coding artifacts. With the Video Quality Experts Group working towards their standardization, NR metrics remain a topic of great research interest.

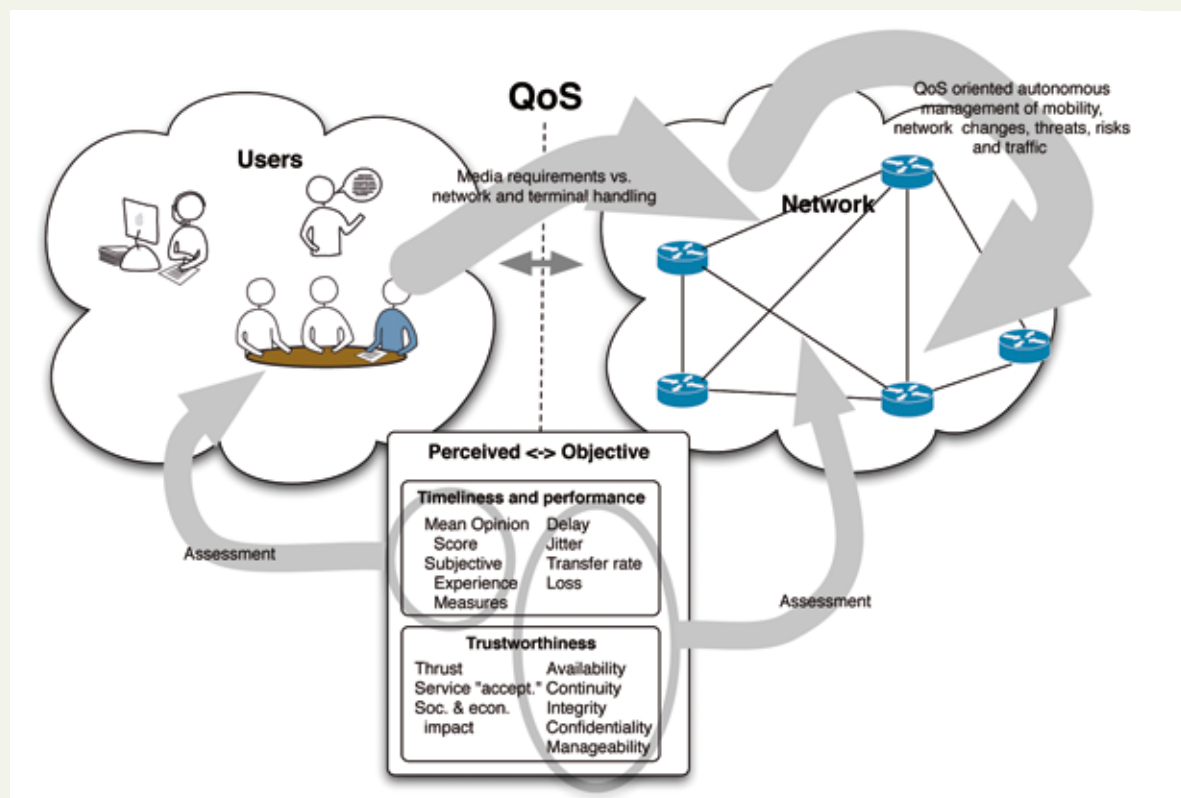


Figure 2. Illustration of the problem domains and the kind of QoS measures addressed in the Q2S research plan.

The effects of delay and packet loss in packet-based transmission have introduced the challenge of handling delays and packet losses. Existing standards for speech coding and video conferencing have been extended to include some form of packet loss concealment but more development can be expected in this area. The delay that is introduced by the packet-based transmission is irrelevant for most one-way transmission applications, but short delay is crucial for two-way communication. From one end to the other, the total delay includes the propagation delay as well as the buffer delays at both ends. The buffers are necessary because of delay variations, packet loss concealment algorithms, and coding and decoding processing delays. Notably, the average propagation delay is normally only a fractional part of the total delay.

For current multimedia communications there already exists a digital media market place, where we all are consumer, be it with our mobile phone, Internet based services or broadcasting. The major challenges arising are in transcoding between formats or even transmoding between media modalities such as speech, audio and video. This requires new ways of content representation, where the methods and functionalities must consider interactivity and adaptive representations of the media. For quantifying quality we need quantitative measures for perception of digital media and the ability to measure this in IP networks. The feedback from measurements can be used to improve the quality in a dynamic way.

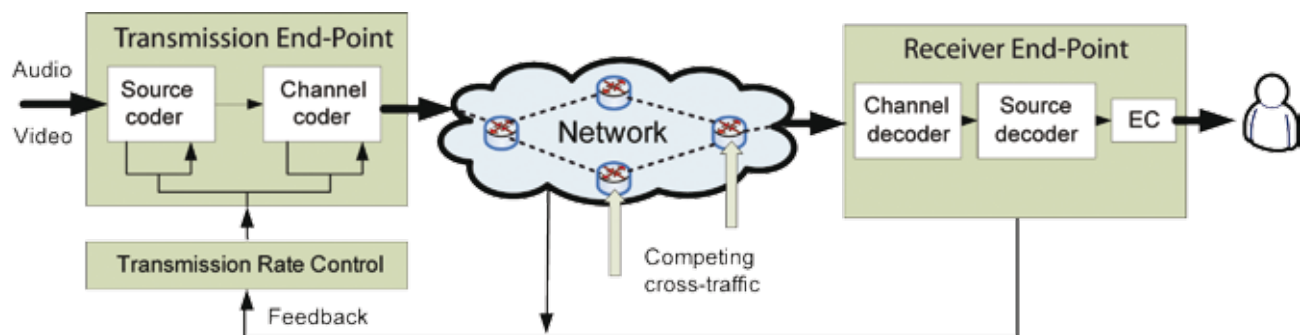


Figure 3. Multimedia services over an IP network.

Centre Director



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Professor at Dept.
of Telematics
(from 2006-01-01
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Multichannel audio

Audio transmission over IP networks opens the way for advanced multichannel audio formats. Such formats can be used for high quality sound reproduction and virtual acoustics beyond today's stereo and surround sound formats, e.g., for video-conferencing with significantly improved sound quality. For multichannel formats, the coding is a central issue due to the growth in bandwidth for an increase in number of channels. This project studies multichannel audio formats for advanced applications that are suitable for communications over IP Networks. Application-dependent requirements, channel correlation, coding aspects, packet loss handling, psychoacoustic phenomena related to spatial hearing, electro- and room acoustic aspects of end terminals are studied in order to optimize format requirements. A focus is placed on the Ambisonics format which has a layered structure. Furthermore, the multidimensional nature of the perception of realistic sound fields requires new quality metrics. Simulations and real perception experiments will be used in this project.

Results this year:

When multi-channel audio is used to accurately represent sound fields in rooms, the complexity grows rapidly with frequency, especially for the diffuse reverberation. This complexity leads to huge bandwidth requirements. At the same time, our perception of details is reduced at high frequency, especially for the diffuse reverberation and this was quantified in listening tests. Only small impairments resulted when three instead of sixteen loudspeakers were used for reproducing reverberation. This potential for reduced bandwidth requirements can be realized if suitable recording/reproduction formats are chosen [58]. When an accurate reproduction is desired, a flexible method was derived that can use arbitrary microphone configurations for a conversion to a transmission format such as Ambisonics [11].

Relations to external projects and activities:

Collaboration with Bård Støfringsdal, PhD candidate at the Dept. of Electronics and Telecommunications, NTNU, in the project "Sound reproduction in virtual acoustics"

Project coordinator: Professor Peter Svensson

Postdoc: Asbjørn Sæbø

PhD candidate: Audun Solvang



PhD candidate Audun Solvang working in Auralab.

Audio in advanced video conferencing

Video conferencing can be used for demanding applications such as playing music together over networks, and other distributed multimedia. This application is very demanding with respect to end-to-end delay and uncompressed audio and video transmission has been used in demonstrations in order to minimize delays. The purpose of this project is to explore possibilities between this raw format with its low latency and high bandwidth requirement, and standard video conferencing formats with higher latencies but efficient compression. Central questions will be the dependence on the application of the involved compromises, which includes packet loss handling, end-to-end delay, and audio quality. Experimental software for audio streaming, as well as video streaming, will be developed. Real perception experiments will be used in this project.

Results this year:

Audio streaming software running under Linux was developed and made available as open-source software. Robust transmission with end-to-end delays below 10 ms is possible when the network delays are minimal and no coding delay is introduced. In a live demonstration between Trondheim and Karlsruhe, uncompressed audio was transmitted two ways with a one-way delay around 40 ms. [44]. The perception of packet loss for

music signals was studied in several listening tests. An existing method for the objective measurement of audio quality has not been developed to handle packet loss, which was confirmed in one of these tests [60]. For the same packet loss rate, a DiffServ-like router lead to slightly higher perceived quality than a Best effort-like router, but only for low packet loss rates. [48]. A technique was developed for the perceptual optimization of unequal error protection of audio over packet networks, by letting the sender simulate the receiver's error concealment [29]. The influence of a delay was studied in a hand-clapping experiment, with two persons clapping a rhythm pattern together. Results showed that a one-way delay of 20 ms had no influence whereas a delay which was 32 ms or longer lead to conditions that were perceived as increasingly worse, and the performance was measurably worse. Hand-clapping is a simple activity which illustrates the difference between speech and music when it comes to the importance of a delay [53].

Project coordinator: Professor Peter Svensson

Postdocs: Asbjørn Sæbø, Snorre Farner

PhD candidates: Erik Hellerud, Jan Erik Voldhaug



Erik Hellerud participates in sound testing by clapping hands.

Scalable and robust coding schemes for IP networks

Packet loss and delay call for adaptive and error-robust coding schemes for multimedia traffic. Many proposed scalable coding formats require complex bit stream manipulation at intermediate locations in the network. Such requirements are unrealistic in present network nodes, so new solutions are needed. Emerging network handling techniques such as prioritization, intelligent packet dropping and congestion control feedback can be integrated into coding schemes in order to change this situation. We will focus our work on scalable and robust source coding techniques that exhibit graceful degradation under error-prone conditions. In general these coding schemes belong to the adaptive source coding domain which includes layered coding, scalable coding and multiple description (MD). These will be investigated in combination with packet prioritization, rate adaptivity and differentiated packet dropping policies. The relations and dependencies between adaptive encoding/rate control in the application and congestion control will be studied and exploited in a joint source/channel coding setup. We focus on techniques that incur a low end-to-end delay, in order to facilitate interactivity and real-time communication services.

Results this year:

We have developed a framework based on joint source/channel coding for the prevention of unfair bandwidth sharing for UDP video. By accurately controlling the relationship between decoded video quality and network/channel state, the implicit incentives for self-beneficial behavior at receivers can be removed. The proposed framework can be used together with existing protocols for congestion control in networks where packet losses are significant during congestion. The framework has been investigated for both unicast and multicast.

Error resilience is an important tool for designing robust coding schemes. We have developed a resilient coding mode for a video encoder (based) which provides rate smoothing and congestion control suitable for video multicast over packet networks. The work includes rate distortion and (power) joint power-rate distortion optimization.

We have worked on a solution for delivering streaming video-on-demand to end-user subscribers via an 802.16 broadband wireless access network, more commonly known as WiMax. The solution takes advantage of features in the forthcoming H.264/AVC Scalable Video

Coding (SVC) scheme, and combines these with a mechanism to perform rate adaptation based on monitoring changes in the amount of flow traffic in the network at any time. Simulation results show that the scheme results in high utilization of the wireless access system. It also maintains smooth transmission rate for the video applications, and ensures that no interruptions in continuous video playback occur during the streaming session, which is essential to ensure that users have a good watching experience.

In the context of multimedia over wireless ad hoc and sensor networks, we addressed multimedia sensor networks (WMSN) as a case study of the multi-source to single-destination (sink) operation concept. We have worked on cross-layer design and optimization for real time transmission focused on energy efficiency and reliability issues involving the link layer adaptation, scheduling and routing. In addition retransmission based streaming techniques are studied over hybrid wireless and wired networks.

A novel slice-based H.264/AVC scheme for video encoding has been designed. The idea is to use an explicit selection of slice mode types to generally avoid large intracoded frames while still providing robustness against packet losses in the network. The employed encoding scheme provides a considerable smoothing of variable bit rate video traffic, resulting in less delay, less delay jitter, and less loss due to buffer overflows and late arrivals. It preserves the efficiency of variable bit rate video encoding, has little overhead, and is in accordance with current video coding standards.

Project coordinator: Professor Andrew Perkis

Professors: Andrew Perkis, Peder J. Emstad, Øivind Kure

Postdocs: Anna Kim and Eren Gurses

PhD candidates: Stian Johansen, Odd Inge Hillestad, Yuan Lin, Anne Nevin, Bjørnar Libæk, Jijun Zhang

Embedded quality assessment metrics for video presentations

In order to be able to monitor and assess the quality of multimedia over IP we will develop several metrics to measure video quality. In particular no-reference metrics that estimate video quality in the absence of a reference video stream can prove to be very useful in monitoring the quality of streamed video. We need

to embed these metrics in the video player in order to improve the perceived quality of video presentations in a Universal Multimedia Access (UMA) enabled system. This leads to our view of QoS driven video players (viewers). At system level we propose to embed these metrics in the delivered bit stream over an IP network so as to use it to enhance the decoded sequence by optimizing de-blocking filters and error concealment for error resilient systems. Our investigations of the embedded metrics will form the basis for setting the requirements of novel multimedia viewers.

Results this year:

This project has come to an end in 2006 with most of the results being accepted for publications in journals scheduled for publication in 2007. Finally, Jijun Zhang defended his thesis "Multimedia adaptation and media conversions for Universal Multimedia Access" in June 2006.



Odd Inge Hillestad on leave, spare time activities at University College Dublin, Ireland.

Project coordinator: Professor Andrew Perkis

Postdoc: Ola Jetlund

PhD candidates: Odd Inge Hillestad, Jijun Zhang

Traffic measurements

Traffic measurements are made to assess the delay and loss through a packet network, and to find the load and throughput of network elements. This is done by having several measurement points and observing and possibly time stamping packets as they pass by. The time stamping is done by using GPS synchronized clocks providing accuracy better than 100 ns. Comparing measurements from different points in the network enables the time delay and possible loss of packets to be found. These measurements are passive measurements and are done at high speed without any disturbance to the traffic. Another type of measurements is active or intrusive measurements. Then probe packets are injected into the network. These packets will inevitably load the network and disturb the traffic. The measurements form the basis for characterizing the traffic offered to the network and for making models. Traffic from video and audio is of particular interest. The metrics used here are different from those used to characterize the perceived QoS of audio and video.

Results this year:

External measurements do not influence the network traffic and lend themselves for measuring router performance. External measurements on a laboratory router have been performed to estimate parameters for network calculus server models. Ongoing work includes measurements with more advanced router configurations including different output schedulers.

Measurements have been done to characterize traffic from the slice-based H.264/AVC scheme developed at Q2S. The encoded video clip was produced by software. The distribution of the scenes and the frames as well as their correlation functions have been studied. These results will then be used to develop traffic models of the video stream. Preliminary results show that the encoding scheme gives a smoother traffic and often performs favourably compared to the standard frame based one.

Preliminary results from the router modelling work have been presented in [T5] and [59].

A multivariate Markov Modulated Fluid Flow model for a bufferless transmission link has been studied to find moments and correlations of congestion periods and cumulative amount of lost bits and lost packets from different sources. Use of a generalized Circulant

Modulated Poisson Process for modeling of correlated traffic has been studied.

Relations to external projects and activities: The LOBSTER project at UNINETT, EuroNGI, WP.JRA.5.1

Project coordinator: Professor Peder J. Emstad

Professors: Peder J. Emstad, Øivind Kure

Visiting professor: Valeriy Naumov

Scientists: Olav Kvittem, Jon Kåre Hellan, Arne Øslebø

PhD candidates: Yuan Lin, Astrid Undheim

Wireless networks

The focal point is QoS in an environment with scarce resources, variable capacity and dynamic topology. The project addresses various aspects of ad-hoc networking where terminals must act as routers in addition to source and receivers. The topology is dynamic, the nodes move and nodes may join and leave the network at will. Ad-hoc networks may be independent networks, or they can be connected to the wired infrastructure through dedicated base stations or gateways. The goal is to offer a similar set of services to those found in the wired network.

Compared to a wired network, QoS in ad hoc network is a somewhat harder problem. In addition to varying load the properties of radio channel itself will vary over time; The channel capacity is a function of the environment and interference from neighbours. The nodes are likely to move, and the topology, capacity and load will therefore change over time. Further, several terminals have access to the media, and privacy is of great concern. QoS in wireless networks therefore represents a challenge.

Results this year:

The work in wireless networks continued with the close collaboration with students and professors at UNIK, Kjeller.

One line of investigation has been multimedia delivery in heterogeneous networks. UMTS/3G networks have a limited capacity for streaming multimedia content to multiple receivers. We have investigated using ad hoc networks based on WLAN interfaces for extending the streaming capacity. This investigation was initiated several years ago, but natural causes (maternity leaves) caused a somewhat slower progression. In the mean time, many UMTS terminals have 802.11 WLAN inter-

faces, and the idea is therefore closer to realization than initially anticipated.

Based on a decentralized protocol, we were able to achieve substantial capacity increase for streaming [23]. The UMTS network was used only for the delivery from the base station to the initial node in an ad hoc network distribution tree. Through this method the UMTS power coverage was reduced substantially. This translates into an overall increase in the carrying capacity of the UMTS cell. The main problem was packet loss due to collisions in the longer ad hoc distribution chains [23]. A natural extension was therefore to investigate whether FEC at the packet level could be of value. At the first node in the ad-hoc distribution tree, additional information is coded into packets that are added to the streaming multimedia content. The information in lost packets can then be recreated from the additional packets inserted into the media flow [24]. Based on standard algorithms, we investigated whether the method could be used to utilize the substantially higher capacity in the ad-hoc network. There was a slight increase in performance, measured in successfully received packets. However, compared to the added load, the benefit was marginal [24].

The second line of investigation is directed towards ad-hoc network used in emergency services where security is mandatory. In 2006 the focus has been on the overall security aspects [3, 27, 28], with particular attention on the key distribution. Previous investigated schemes on routing relied on cryptographic methods for authentication. The underlying assumption was that the nodes had methods for key distribution and key revocation. The investigation on key distribution was initiated earlier, but all results were published in 2006. The main results were an analysis of existing schemes [3], a proposal for key distribution in ad hoc network [28], and an overall analysis of identity based schemes [27]. The results for key revocation were published in 2007 and will be reported in next years report.

Finally, the investigation into QoS architecture for ad hoc networks was continued [55]. The focus is the integration of ad-hoc network with fixed networks. Ideally, the standard Diffserv architecture could be extended into the ad-hoc networks. However, this requires additional mechanisms, due to the inherent variability of the ad-hoc network. The goal is to make these additional mechanisms as transparent as

possible [55]. The focus has so far been on identifying the necessary additional mechanisms.

We have continued the work on spatial stochastic models in two areas, i) modeling the traffic load in dense wireless multihop networks [32, 36], and ii) modeling the mobile user behavior [33]. The models for wireless multihop network provide insight into what happens in the limit when the number of users in the network is large. Understanding the models of mobile users is important, e.g., for the performance analysis of mobile networks by means of simulations.

Fountain codes is a new concept for efficiently transferring large amounts of data over erasure channels. During this year our efforts with regard to this area focused on studying a specific type of fountain codes called LT codes [54]. In particular, we were interested in optimizing the so-called degree distribution of LT codes, which is the key parameter behind the encoding procedure and essentially defines the performance of the code.

Relations to external projects and activities:

EuroNGI, WP.JRA. 2.4, COST 290. Collaboration with Knut Øvsthus FFI/UIO, Eli Winjum, Mariann Hauge, Pål Spilling, Leif Nilsen, UIO, UNIK

Project coordinator: Professor Øivind Kure

Professors: Øivind Kure, Peder J. Emstad

Postdoc: Esa Hyytiä

PhD candidate: Tor Kjetil Moseng

Congestion control and service differentiation

Audio, video and multimedia services impose strict (real-time) requirements on the loss, jitter and delay through the network. Some lesser requirements are set for services such as web browsing, transactions and e-commerce. To meet these requirements, the routers use different traffic handling for the packets. For IntServ this is done on a per flow basis while for DiffServ it is done on a class basis. The latter therefore scales better and it is the preferred architecture in the Internet. With Diffserv, the packet handling is divided into two sets of tools, the scheduling of packets, and the discarding of packets when buffers reach certain thresholds. In order for Diffserv to be used to offer end-to-end QoS, the traffic load must be limited. This can either be done through adaptable applications or admission control. Congestion control signals, either as

dropped packets or by the marking of packets, can be used to signal congestion to the sources and thereby let them adapt to the situation. This requires cooperation with the encoding at the source. Audio and video sources are studied for this purpose. Appropriate models of the sources have to be made, policies worked out for service differentiation in a router, and measurements taken.

Results this year:

The project has worked on methods to estimate the available capacity on a media distribution path. The estimate will be used to control unicast variable rate video streaming.

Knowledge about the dynamic behavior of sources and nodes is necessary to exercise congestion control. The fluid-flow approximation of the streamed traffic with sources modeled as ON-OFF sources has been taken further to encompass dynamic behavior of the queue. Of interest has been the time periods with full and empty queue, and the time periods to empty and fill up the queue. The Laplace-Stieltjes transform of the pdf's of these time intervals of interest are found, and the moments of the congestion and empty periods of the buffer are obtained. Further, the moments of the recurrence times between these empty and congestion periods can also be found.

One particular topic that has large amount of attention within the research community has been the popular transmission control protocol (TCP) used in the Internet. With performance analysis of IP router(s) in mind, in [34] we developed a new elementary fluid flow model for TCP congestion control, which captures the correlations between the different concurrent TCP flows. The model was further analyzed in [35].

Relations to external projects and activities:

EuroNGI, WP.JRA. 2.1 and WP.JRA. 2.2,

Project coordinator: Professor Øivind Kure

Professors: Peder J. Emstad, Øivind Kure

Postdoc: Esa Hyttiä

PhD candidates: Erling Austreim, Bjørnar Libæk

Engineering for real-time services in NGI

Next Generation Internet (NGI) will offer a multitude of services, some of which have real-time requirements

such as audio, video and multimedia, and should do this with an acceptable QoS. New knowledge is needed to do the required design, planning, dimensioning, and management. Service Level Agreements (SLAs) will be the contracts between network operators/service providers/users and should describe all relevant aspects of QoS that can be expected. Several architectures like IntServ, DiffServ and MPLS are proposed to achieve these goals, but the proposals need further studies. Service differentiation is a key issue, but how to give end-to-end guarantees with respect to loss and delay needs much further research. In addition to service differentiation, admission control and possibly resource reservation are measures to be taken. The admission control schemes must be studied together with measures taken for congestion control. Laboratory experiments and model-based studies are needed to evaluate the various approaches.

Results this year:

The DiffServ architecture focuses on a scalable design where flows are aggregated at each router to be given a certain QoS level. For admission control however, no approach is specified by the DiffServ standard. The paper [37], presents a framework approach, called implicit admission control (iAC), to be used in a DiffServ network. The key idea of this approach is to let each packet of a flow carry both its service requirement and (possibly coarse) traffic information. The router can perform admission control without the need of explicit signaling and is a scalable and therefore promising design. This framework uses measurement based admission control (MBAC), which still leaves some open problems regarding how to properly do the measurements needed for the decision making. We are currently in the progress of investigating new traffic characteristics for MBAC and the design of on-line algorithms for measuring such characteristics. The ongoing work will lean on simulations and possibly lead to implementations on a real test-bed.

Relations to external projects and activities:

EuroNGI, WP.JRA.2.1, WP.JRA.2.2

The cooperation with Professor Yuming Jiang, at ITEM, NTNU, is continued.

Project coordinator: Professor Peder J. Emstad

Professor: Peder J. Emstad

PhD candidate: Anne Nevin

Probabilistic assessment of security services in dynamic environments with non-trusted parties

Results this year:

A new approach to integrated security and dependability evaluation, which is based on stochastic modeling techniques, has been developed [42]. The aim is to provide operational measures of the trustworthiness of a system, regardless whether the underlying failure cause is intentional or not. By viewing system states as elements in a stochastic game, we can compute the probabilities of expected attacker behavior, and thereby be able to model attacks as transitions between system states. The proposed game model is based on a reward and cost concept. How the expected attacker behavior is affected by the parameters of the game is analysed. The model opens up for using traditional Markov analysis to make new types of probabilistic predictions for a system, such as its expected time to security failure. Tools for monitoring the security state of assets in a network are an essential part of network management [22]. Traditional risk assessment methodologies provide a framework for manually determining the risks of assets and intrusion detection systems can provide alerts regarding security incidents, but these approaches do not provide a real-time high level overview of the risk level of assets. A previously proposed real-time risk assessment method to facilitate more flexible modeling with support for a wide range of sensors has been extended. Specifically, a method for handling continuous-time sensor data and for determining a weighted aggregate of multi-sensor input has been developed.

PhD candidate André Årnes successfully defended his PhD-thesis: Risk, Privacy and Security in Computer Network, December 15, 2006.

PhD candidate Karin Sallhammar has submitted the first draft of her PhD-thesis: Stochastic models for combined security and dependability evaluation.

Relations to external projects and activities:

EuroFGI, WP.JRA.6.3 Security.

Project coordinator: Professor Svein J. Knapskog

Professors: Bjarne E. Helvik, Svein J. Knapskog

PhD candidates: Kjetil Haslum, Karin Sallhammar, André Årnes

Security services in dynamic network environments for mobile users

Results this year:

There is a need to provide secure cryptographic services in dynamic network environments with untrusted parties and a changing net topology. Cryptographic services are security services implemented by cryptographic mechanisms, examples of such services are confidentiality, authenticity, integrity, privacy, accountability, accessibility and non-repudiation. Privacy is a service that is often difficult to realize at the same time as other cryptographic services, like authenticity, accountability and non-repudiation. Parties in dynamic networking environments like mobile ad hoc networks, where each node is acting as a combined terminal and router, would be particularly exposed to threats against their privacy since they have no control over the trustworthiness of network nodes that handle the messages sent. Appropriate privacy enhancing cryptographic mechanisms, that can be trusted to work as intended, are required to handle this problem. Some of the research in this area focuses on building a probabilistic security model for routing in dynamic networks which allow for quantification of the security offered by the protocols.

One line of research in this project has been the construction of new cryptographic primitives, both for confidentiality and integrity services. In one paper [submitted to ACISP 2007] is shown how the synchronous stream cipher Edon80 - proposed as a candidate stream cipher in Profile 2 of the eSTREAM project, can be efficiently upgraded to a synchronous stream cipher with authentication. This is achieved by simple addition of two-bit registers into the e-transformers of the Edon80 core, an additional 160-bit shift register and by putting additional communication logic between neighboring e-transformers of the Edon80 pipeline core. This upgrade does not change the produced key stream from Edon80, and it is assumed that in total it will need not more than 1500 extra gates. Another angle is to attack the long standing problem of providing integrity and confidentiality using essentially the same algorithm. The feasibility of such an approach has been demonstrated in [19]. The paper describes a method for joint encryption and error-correction coding, named here as Cryptcoding. Cryptcoding is a procedure in which encryption/decryption and error-correction coding/decoding are performed in a single step.

There are obvious advantages of this approach over the traditional First-Encrypt-Then-Encode approach.

Relations to external projects and activities:

EuroNGI, WP.JRA.6.3 Security.

Project coordinator: Professor Svein J. Knapskog

Professor: Svein J. Knapskog

Postdoc: Danilo Gligoroski

PhD candidates: Marie Elisabeth Gaup Moe

QoS management by emergent behavior

The project explores the principles for, the feasibility and the quantitative properties of applying emergent behavior to provide QoS. As a basis for this, efficient resource utilization in distributed communication systems is required. (Emergent behavior, in this context, is global behavior seen from the individual service users and the network as a whole, emerging from a (large) number of simple, loosely coordinated actions/behavior by agents/network elements/etc.) This may be regarded as a distributed stochastic optimization problem. From the rare event theory based on the cross-entropy optimization principle, simple agent behavior is derived, which finds good solutions to NP-hard problems, and with added heuristics, this deals well with QoS management issues. Providing availability, continuity, etc. of services tailored to requirements, i.e. dependability differentiations, are an important aspect of future service provision. These aspects are addressed in this project primarily with emergent techniques.

Results this year:

It has been demonstrated feasible, at least for small networks, to perform network dependability analysis taking the dynamic behaviour into account. The modeling is based on stochastic activity networks (SAN) with an explicit state space truncation included in the model. Results are obtained for distance vector routed networks [15]. A hybrid analytical simulation technique is derived for analyzing shared backup path protected (SBPP) networks, where paths are found by the emergent CE-ant technique [16]. The factors influencing the unavailability in these schemes are studied [17].



PhD candidates Anders Mykkeltveit and Laurent Paquereau.

Our method for CE-ant based path finding are extended by the ability to adapt the ant generation rate and strategies to reduce overhead and decrease convergence times [24], [25]. The CE-ant technique is also considered for use in wireless mesh networks. Towards investigations of this, a module-based wireless node for NS-2 with an increased set of capabilities is developed [37]. This module is put in the public domain.

NS-2 is also used in a first attempt to introduce splitting/RESTART in a general object oriented simulator [54]. The objective of this is to be able to simulate, in reasonable detail, networks providing differentiated dependability. The options for introducing improved interdomain dependability as a part of an end-to-end differentiation scheme is identified [55]. In co-operation with AGH, an extensive survey of resilience differentiation frameworks in communication networks has been performed.

Relations to external projects and activities:

EuroNGI, WP.JRA. 2.3 and 3.3; Informal cooperation with Future & Emerging Technologies project (IST-2001-38923) BISON (Biology-Inspired techniques for Self-Organization in dynamic Networks) which concluded in April 2006.

Project coordinator: Professor Bjarne E. Helvik

Professor: Bjarne E. Helvik

Postdoc: Otto Wittner, Crina Grosan

PhD candidates: Qitao Gan, Anders Mykkeltveit, Laurent Paquereau.



Qitao Gan is about to conclude his dissertation.

QoS in burst and packet-switched optical networks

DWDM optical networks offer a huge increase in capacity and combined with optical switching, very efficient transport services may be provided. Research on burst and packet-switched optical (OBS and OPS) networks is initiated to overcome the lack of flexibility in OCS (optical circuit switched) networks. In these networks the design constraints from the optical technology are different from those traditionally met in packet-switched networks. For instance, buffering of data in the optical domain is at best inflexible and cumbersome and the switching costs become relatively much larger than transmission costs compared to "electronic" networks. This raises new challenges in comprehending as well as in the design and dimensioning of these networks to achieve a required QoS cost efficiently. The project addresses these challenges.

Results this year:

Part of the work in this project has been carried out in close co-operation with the OpMiGua project where dependability differentiation aspects of the the OpMiGua architecture has been studied [43]. A substantial fraction of the work done internationally on of resilience differentiation has been dealing with optical networks, and the work reported under "QoS management by emergent behavior" has strong relations to this project as well. Studies of the architecture with multihoming of the electronic in- and egress unit for tolerance of

node and link failures, continues with finding optimal solutions for general topologies. This work is not yet concluded.

Relation to other projects:

Optical Migration Capable Networks with Service Guarantees [OpMiGua] with partners Telenor, NTNU - Departments Electronics and Telecommunication and Department of Telematics, and Network Electronics ASA.

Project coordinator: Professor Bjarne E. Helvik

Professor: Bjarne E. Helvik

PhD candidate: Anders Mykkeltveit

Dependability assurance in distributed systems

Distributed computing has the potential of providing highly dependable services by having replicas of the server processes on several nodes in the network. This technology is relevant for network internal services (e.g. network management) as well as external services (e.g. e-commerce). Keeping consistency between replicas is demanding and introduces performance penalties. Fault transparency, one of the virtues of distributed computing, also requires management functionality, which is critical for the QoS, both during fault handling and normal operation. The project studies the means to provide trustworthy services by this approach and the quantitative evaluation of the QoS obtained. The work has so far been focused on QoS related management in the Jgroup/ARM platform and experimental evaluation.

Results this year:

The effort this year has been on writing a summary publication presenting the Jgroup/ARM system and demonstrating its capabilities. Some work on load distribution for controlled QoS started toward the end of the year.

Relations to external projects and activities:

The Jgroup/ARM Project, in cooperation with University of Bologna and University of Stavanger.

Project coordinator: Professor Bjarne E. Helvik

Professor: Bjarne E. Helvik

Postdoc: Crina Grosan

Anders Mykkeltveit and Bjarne E. Helvik

Abstract

Traditionally, the Internet has been used for best-effort traffic. The introduction of new services that have different Quality of Service (QoS)-requirements yields a need for the network operators to be able to offer different service levels. An important QoS-factor is dependability, e.g. the provision of services with a certain maximum accumulated downtime per year or guaranteed long periods of uninterrupted service. In this paper we investigate whether it is feasible for a provider to offer his customers the choice of differentiated levels of dependability. Most recent research on dependability differentiation focuses on intradomain networks. In order to introduce end-to-end differentiation over the Internet, differentiation must also be supported at the interdomain level. Studies on the behavior of interdomain routing show that the Internet cannot currently offer the level of dependability needed by customers or applications with high requirements. We therefore need mechanisms that can increase the availability for interdomain routes. These techniques may be used as a basis for differentiation by offering the improved level of dependability exclusively for high priority traffic. In this paper we present the challenges related to interdomain routing and review the literature on techniques to improve dependability at the interdomain level. We discuss how differentiation may be introduced at the interdomain level using the proposed improvements to interdomain dependability.

Introduction

In the future next generation Internet, different applications with different QoS requirements are expected to be carried in the same network. An important QoS factor is dependability, e.g. that the service should be available when needed, be delivered without interruptions as long as needed and that down periods have a low upper bound. For communication services the dependability is related to the network's ability to tolerate faults, such as cable cuts and equipment failures, and it relates to the correctness of network protocols, operation and maintenance.

Since different customers and different services have different dependability requirements, e.g. probability of finding the service operational when needed, the provider is interested in mechanisms that allow him

to differentiate the level of dependability offered to different customers. Improving the dependability is expensive since redundant resources are needed, but if some customers are willing to pay a higher price for better service, this may generate revenue for the operator.

The Internet is composed of a large number of networks. Each network is managed and operated by a company or organization and is denoted an Autonomous System (AS). The network operator has full control over the resources in his own network, and he may provide different levels of QoS for the traffic inside the AS. Several frameworks for providing differentiated dependability inside an AS have been proposed in the literature, see [4] for an overview. A customer with high dependability requirements is likely to expect the same level of dependability for all his connections, whether they are with other customers connected to the same network, or if they are connected to a network operated by another provider. The frameworks for differentiated dependability only consider a single AS and are not easily extended to the challenges imposed by interdomain routing. In particular, the frameworks will suffer severe scalability problems, and they rely on a global view of the network they operate in, which is not consistent with the network operators' decisions about keeping information on their network hidden from the outside world. There is therefore a need for new frameworks that can allow the introduction of differentiated dependability in the Internet.

The dependability of interdomain paths has been studied for many years. The availability is the probability that a service is working at a random point of time. The results show that the Internet cannot currently offer the level of availability needed by customers with high dependability requirements. A measurement study [25] found that the probability of encountering a routing pathology was between 1.5% and 3.3% in 1994–1995. A more recent study indicated that the situation has not improved much since then [11]. In addition to availability, some services will have requirements on the duration of the outages, and the time between failures. While some services are unaffected by short failures, other services like tele-surgery will have very strong requirements on continuity of the service. Unfortunately, failures are reported to be frequent, and although many failures are short a significant percentage of them last more than 2 minutes [7].

Recently, some research has been devoted to techniques for improving the dependability for interdomain paths. The adoption of some of these suggestions would introduce the possibility to give a positive differentiation if the mechanisms were only applied for traffic with high dependability requirements.

The objective of this paper is to investigate the challenges related to providing improved and differentiated dependability in the interdomain level and to investigate mechanisms proposed in the literature for achieving this. We discuss the feasibility of using these mechanisms as a basis for dependability differentiation at the interdomain level. To the authors' knowledge, this is the first attempt to compare and investigate the existing literature in this area. The paper is organized as follows. In Section 2, we present the concept of interdomain differentiation. Section 3 introduces the reader to the state-of-art in interdomain routing. Section 4 presents an overview and comparison of the literature of improving interdomain dependability. Section 5 gives concluding remarks.

Dependability Differentiation in interdomain networks

In this paper, we are interested in investigating whether an Internet Service Provider (ISP) can offer his customers the choice between multiple levels of depend-

ability. The dependability seen from a customer is the end-to-end dependability for all his connections. These connections span access networks, and the networks of one or more ASes. The routing inside an AS is referred to as intradomain routing, and the routing crossing multiple ASes is denoted interdomain routing. Intradomain, interdomain and access networks can all be regarded as different research areas for dependability differentiation. Figure 1 shows the scopes of these three areas.

The need for dependability differentiation has spurred a lot of research, but so far this research focuses on a single AS. It is convenient to limit the scope of differentiation to the intradomain level, since the operator has full control over his own network. However, since most connections in the Internet span several ASes, we believe that dependability differentiation is also needed at the interdomain level in order to provide a real difference to the users. As a minimum, it should be possible to establish some paths with a higher level of dependability through the Internet. Interdomain routing poses a number of additional challenges compared to intradomain routing, and these challenges have to the authors' knowledge not been directly addressed in the context of dependability differentiation.

For real end-to-end dependability, the access network all the way to the customer premises should be inclu-

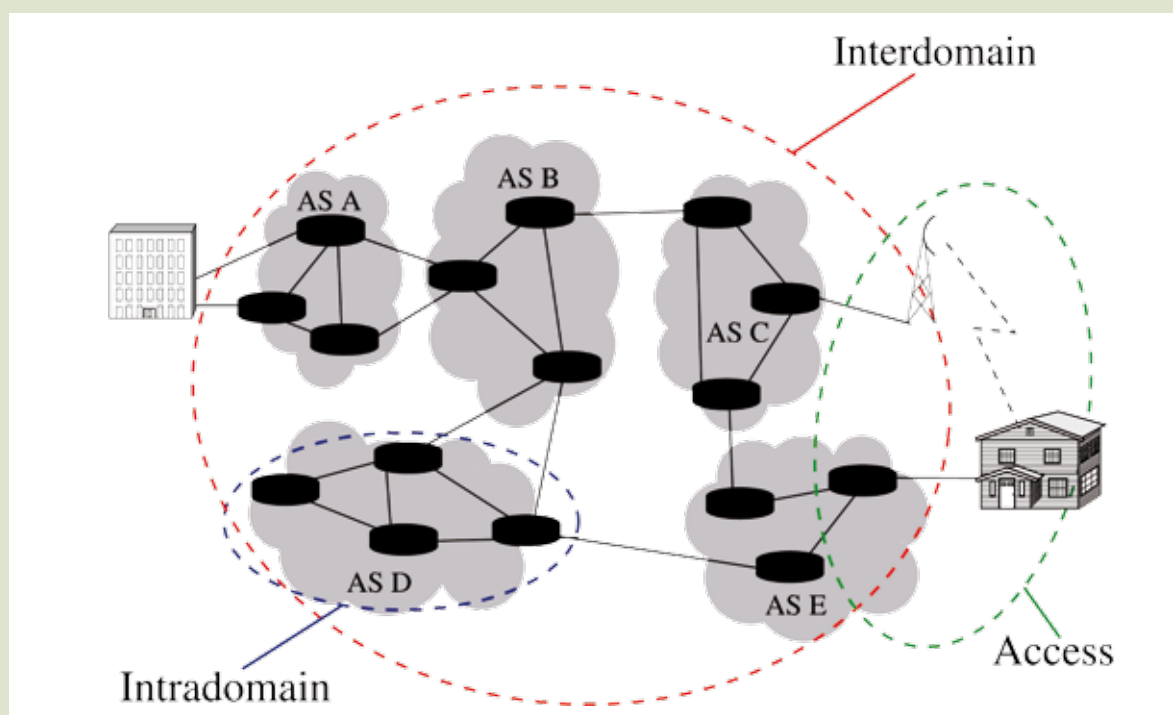


Figure 1. Research areas in end-to-end dependability differentiation.

ded since it will probably be the dependability bottleneck for the Internet connection. The customer can be multihomed either to two service providers or with multiple links to the same provider. We focus on a situation where one ISP provides a dependable service to the end-users. We therefore assume that the customer is connected with at least two independent physical links to his ISP, and that the ISP has implemented support for providing a dependable service of packet transfer through his network from the user's access links and to the network border toward other ASes.

Interdomain routing

The Internet is composed of a large number of networks, denoted ASes. Each AS is managed independently by a company or organization. Internally, the operator runs an interior routing protocol. In pure IP-networks, protocols such as OSPF [24] or IS-IS [17] are used, and packets are forwarded on a hop-by-hop basis. Other networks use connection-oriented technologies such as Multi-Protocol Label Switching (MPLS) or Generalized Multi-Protocol Label Switching (GMPLS) to establish Label Switched Paths (LSPs). With respect to differentiation, the connection-oriented approach seems most suited and has been the focus for most research.

To allow traffic to traverse network boundaries, operators must connect their networks and agree on the terms for data transfer. The two most common relations between ASes are provider-customer and peer-to-peer. In a provider-customer relationship, a provider transports traffic to and from its customers to give them access to the rest of the Internet. The customer AS is charged for the transport service. ASes that have a peer-to-peer relationship have agreed to forward traffic between their customers, usually without charging each other.

Figure 2 shows a graph representing six ASes and the relations between them. Provider-customer relations are indicated by solid-lined arrows. In the figure, AS C is a customer of AS E and a provider for AS A. The dotted arrow between AS C and AS D indicates that they have a peer-to-peer relation, allowing traffic from AS A to AS B to traverse peering link. The relations between the ASes give the Internet a hierarchical structure. ASes that do not have any customer ASes are denoted stub ASes. The stub ASes are typically ISPs.

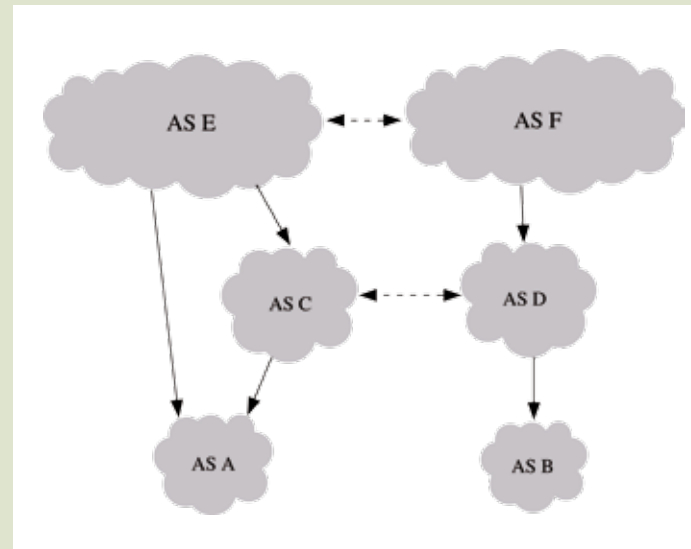


Figure 2. ASes and relations.

Multihoming at the AS-level is frequently used to increase the availability of a network or for load-sharing. This means that a customer is connected to multiple providers. In figure 2, AS A is connected to two providers, a special case of multihoming denoted dual homing.

The business-relationships between the ASes are reflected in routing policies which are configured in the routers. A multihomed provider may choose to forward most of its traffic to the one of his provider that offers the lowest price for the transit service. This will affect which routes the operator advertises to his customer networks, and the outcome of the policy could be that the path toward the destination is inflated [10]. An important result of policy configuration is that not all paths that are physically possible may be used for transporting data.

Studies on the Internet topology have found that the AS-degree (the number of connection points between an AS and other ASes) follows a power law [5]. This means that there are a large number of networks with low AS-degree and a small number of transit networks at the top of the AS-hierarchy with very high AS-degree. Today the internals of the ASes are hidden from other ASes for many reasons, and this makes it difficult to introduce mechanisms to enhance the performance of the network at large since no information on capacities, redundancy and congestion is exchanged between the ASes.

The huge number of ASes in the Internet today, in addition to the expected continued growth, indicates that scalability is one of the most important requirements for the interdomain routing protocols [8, 34]. It seems unlikely that one entity will be able to have or allowed to have a global control over the routing of the Internet.

Current practice -BGP

The current de facto standard interdomain routing protocol is the Border Gateway Protocol (BGP) [28]. The key idea of BGP is to allow exchange of network reachability information between BGP routers. The destination for a BGP route announcement is expressed with an IP address prefix. The announcement contains the path of ASes used by the announcing router to reach the destination prefix. BGP is divided into an internal and an external protocol. The internal protocol is run between routers in the same domain. They exchange information on reachability they have received from other networks and decide on which is the best if a network can be reached via multiple paths. Normally, all BGP routers have peering sessions with all the other BGP routers in the same AS. In large networks, the number of internal sessions is reduced by applying route reflectors that mediate this communication.

Each AS has one or more edge routers that communicate with edge routers of neighbor ASes. These routers run an external routing protocol which is used to exchange routes to all other networks in the Internet and to routers in their own network, all depending on their policies and agreements. In figure 3, internal routing sessions are indicated by dotted arrows while external sessions are indicated by solid arrows.

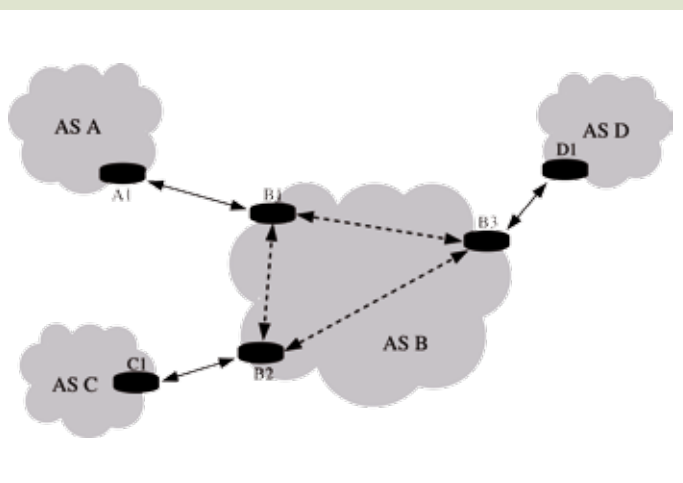


Figure 3. Internal and external BGP.

When a BGP router looks up the route for a packet, the longest matching prefix is always selected. If more than one path to a destination is found in the router's database, the routing policies are checked to see if one route is preferred over the other. If there is still a tie, the shortest path, measured in the number of ASes it traverses is chosen. Finally some tie-breaking rules are applied. This is in effect a random process. Each BGP router normally only announces the routes they use themselves, so each router has an incomplete view of the overall network topology.

With BGP, failures are detected by a BGP router when it loses contact with one of its peers. It then sends out UPDATE messages to its remaining peers. The update message could contain a withdrawal of the routes that are affected by the failure. The news about the route withdrawal must be propagated throughout the Internet. If an AS is multihomed, its BGP routers may have information on other routes to the destination. They can send out UPDATE messages containing the new routes to their peers.

Measurement studies have found that the time taken for all the BGP routers to converge to a consistent view of the topology can be in the order of several minutes. During this convergence process, packets are highly likely to be dropped at some point, but they may also reach the destination via fluctuating paths [20]. The QoS for applications using paths that are converging can be so degraded that the route should be considered as down.

It has been observed that a single failure is typically announced many times, and that several rounds of route updates are needed before convergence is reached. Today it is common for peers to extend the peering agreement to include forwarding of traffic as a backup solution if the provider link fails [3, 9]. BGP can announce backup routes that span one or more peer links if both ASes have agreed on this.

Interdomain traffic engineering

Network operators have the possibility to manually configure routing in their ASes to minimize the cost of traffic forwarding. One common strategy is early-exit (or hot-potato) routing which is used if a multihomed AS has multiple routes to a destination. The idea is simply to forward traffic to the nearest egress router from the incoming router. While this type of routing can reduce the costs for one operator, it can certainly

increase the cost for other operators, and might also result in a higher global cost of routing.

Announcement of redundant routes is used for interdomain traffic engineering. A dual-homed stub AS may prefer to share the load of incoming traffic over its provider links. This can be done by announcing an address prefix corresponding to one half of the address space to one provider and the other half to the other provider in addition to announcing the full AS-prefix. With this arrangement, the load is shared under normal operation since the ASes will route packets based on the most specific prefix. If one of the provider links fail, the traffic going over that link can be sent over the other link since the full AS-prefix is now the only available route to the destination AS [26].

A framework where neighbor ASes negotiate on the use of the links between them is suggested. The idea is that it should be possible to find better routing configurations for both networks than the default (early-exit routing) case where no negotiation is used [23].

There has been some research on how to provide differentiated traffic handling performance in the Internet [22, 32]. The challenges faced here are similar to what we face with dependability differentiation. The most important requirements to new architectures are scalability in addition to the requirements from the business relations between the ASes in the Internet.

Improving interdomain dependability

Some research has been directed toward improving dependability at the interdomain level. Differentiation is not mentioned explicitly, but some techniques can be applied to only parts of the traffic, thereby implicitly introducing (at least) two dependability levels. Figure 4 shows a decomposition of the principal methods used to improve interdomain dependability. The presentation of the literature on interdomain dependability is organized according to this figure. The first classification is whether the proposed methods use a single or multiple interdomain (AS-level) routes to improve dependability. In the first case, the suggested methods try to improve the dependability of routes so that failures of links and routers do not result in a route failure. In the second case, the methods take advantage of the existence of multiple paths at the AS level so that when one path fails, data can be switched to another path.

Single AS-path

These approaches aim to reduce the number of route changes that are announced globally by strengthening the paths. If faults can be handled locally by the ASes that are members of the path, the failure may not need to be announced outside the neighborhood. This will reduce the frequency of BGP updates which lead to the slow convergence process.

Methods for strengthening single AS-paths may be implemented using different underlying technologies.

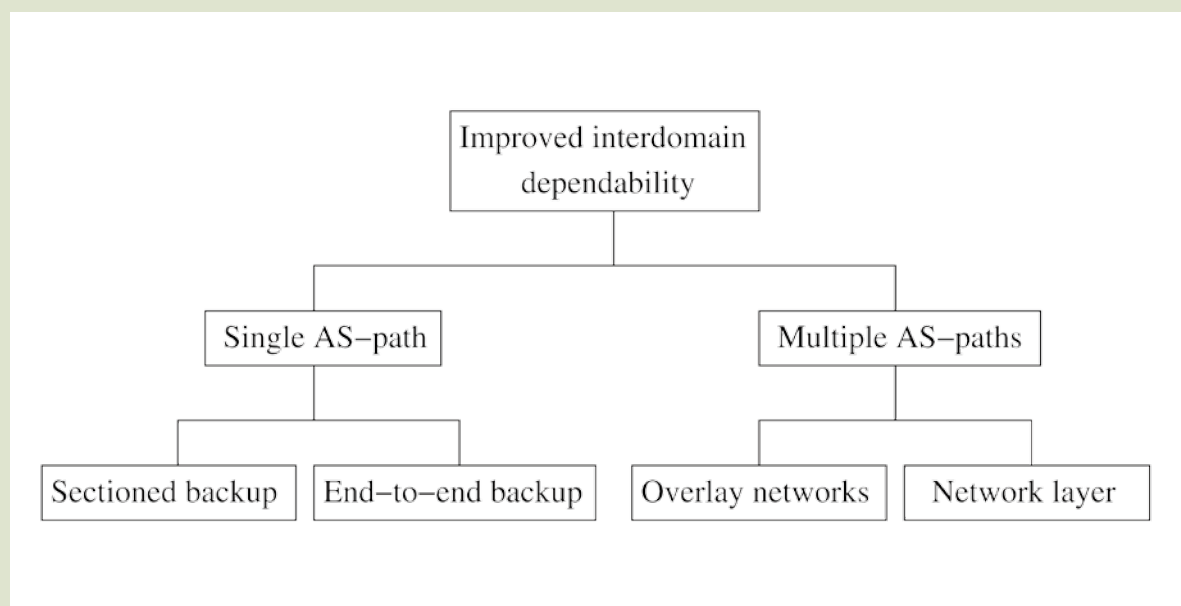


Figure 4. Proposed methods to improve interdomain dependability.

In the literature, both connection-oriented approaches using MPLS LSPs and methods based on IP-restoration have been proposed. In general, MPLS protection will give faster recovery than IP-restoration. In MPLS networks, capacities might be dedicated so congestion is avoided when switching to the backup path. If the connection-oriented (MPLS) approach is used, all the ASes must have the same underlying technology. This will typically limit the possibilities of using these techniques end-to-end in the Internet, and these techniques are therefore most easily applied inside large networks that are divided into multiple domains, or in a small neighborhood of cooperating ASes.

The single AS-path approaches can be divided into two classes depending on the scope of the backup paths that are used in case of failure. With sectioned backup, the backup paths have limited scope, restricted to two neighbor ASes in the path. With global backup, the backup paths are disjoint from the source AS to the destination AS.

Single AS-path with sectioned backup

A scheme using MPLS to provide local backup LSPs in case of failure to the infrastructure connecting two ASes was proposed by Huang and Messier [15]. They propose to improve the reliability of BGP-connections by allowing adjacent ASes to cooperate by establishing local MPLS backup paths crossing the domain boundary between them. The approach assumes that there exists at least two independent links between each neighboring AS in the path. An example configuration of the LSP-arrangement resulting from this approach is shown in figure 5. The primary path (solid line) is protected by different backup LSPs (dotted lines). The backup path arrangement is able to protect against all single failures of a link or router in the primary LSP. The minimal number of backup paths that are needed for each primary path in each transit AS, like AS B in the figure, is two.

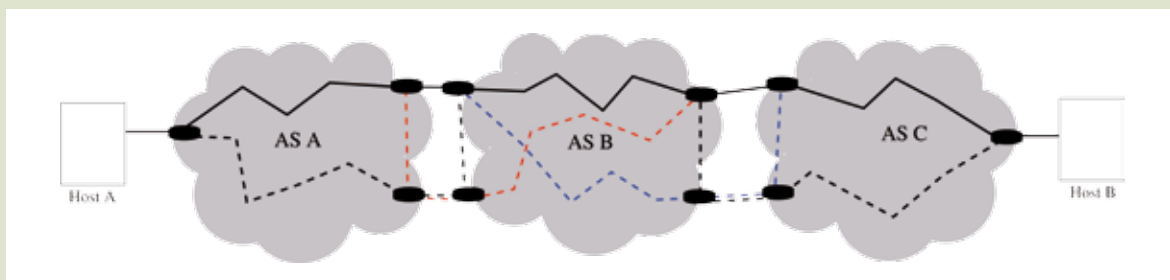


Figure 5. Single AS-path with sectioned backup.

It has been suggested to allow backup LSPs via ASes that are not in the single path announced at the BGP level [27]. It is suggested to attach a recovery IP address to each AS in the AS-path in the BGP route announcements. The recovery address belongs to a router in an AS that is different from the next hop in the AS-path. Figure 6 shows an example where a backup path for failures in AS B goes via AS D.

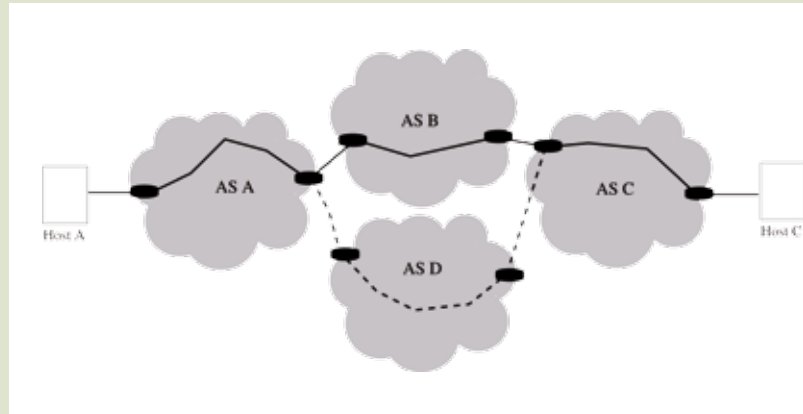


Figure 6. Backup paths via AS not in currently used route.

In [6], several ideas for strengthening a single AS-path using IP restoration are presented. First of all, failures inside an AS should be recovered by IP rerouting without altering the AS-path announced by BGP. Second, the interconnection infrastructure between all neighbor ASes should be redundant, so that failures at the inter-AS links and edge routers can be recovered by IP-level mechanisms. When the two former approaches fail, a temporary reroute through a third AS could be allowed, resulting in the same route pattern as shown in figure 6. The information on the route change is not propagated via BGP unless it persists for some time. A potential problem with this approach is that it may cause policy violations for a short time period since some ASes will not accept to have their traffic sent

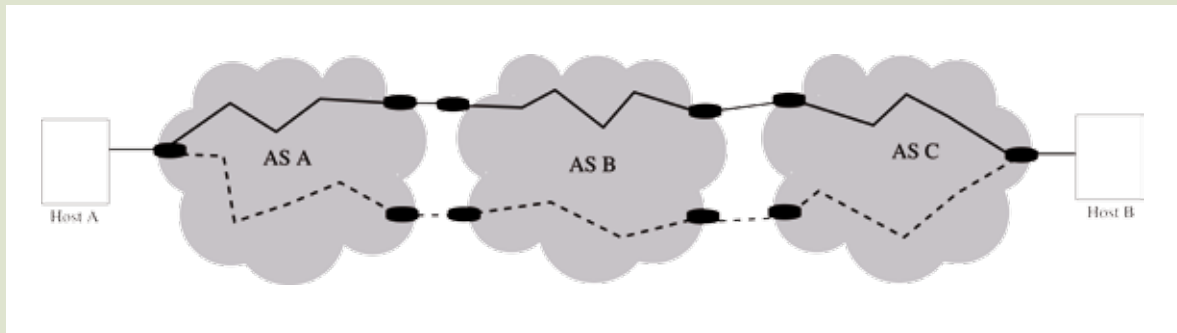


Figure 7. Single paths with end-to-end backup paths.

through the third AS that provides the local backup. In cases where the failure cannot be recovered locally, ordinary BGP UPDATE messages with withdrawals of the affected routes are initiated.

Single AS-path with end-to-end backup

These approaches use BGP to find AS-paths, but MPLS is used to set up disjoint primary and backup paths through the AS-path. Currently, there exist drafts that suggest how to establish link and node disjoint paths through an AS-chain [29]. The resulting primary and backup paths are shown in figure 7.

It should be noted that segments of the backup paths might be allowed to traverse different ASes than the primary path. In [30], the existence of two partially AS-disjoint BGP routes in the originating AS is used to set up LSPs that are AS-disjoint until they merge.

Multiple AS-paths

These approaches aim to take advantage of the existence of disjoint paths at the AS-level. By assuming that the failure processes of the ASes are independent, the probability of finding two (or more) paths unavailable is reduced. We divide the approaches using multiple AS-paths into two categories; overlay networks that operate on top of the current Internet and approaches that operate at the network layer.

Overlay Networks

Overlay networks are “networks on top of networks”. An overlay network consists of nodes that communicate with a protocol using the underlying network. Overlay networks is a general technique that does not intervene with the underlying infrastructure.

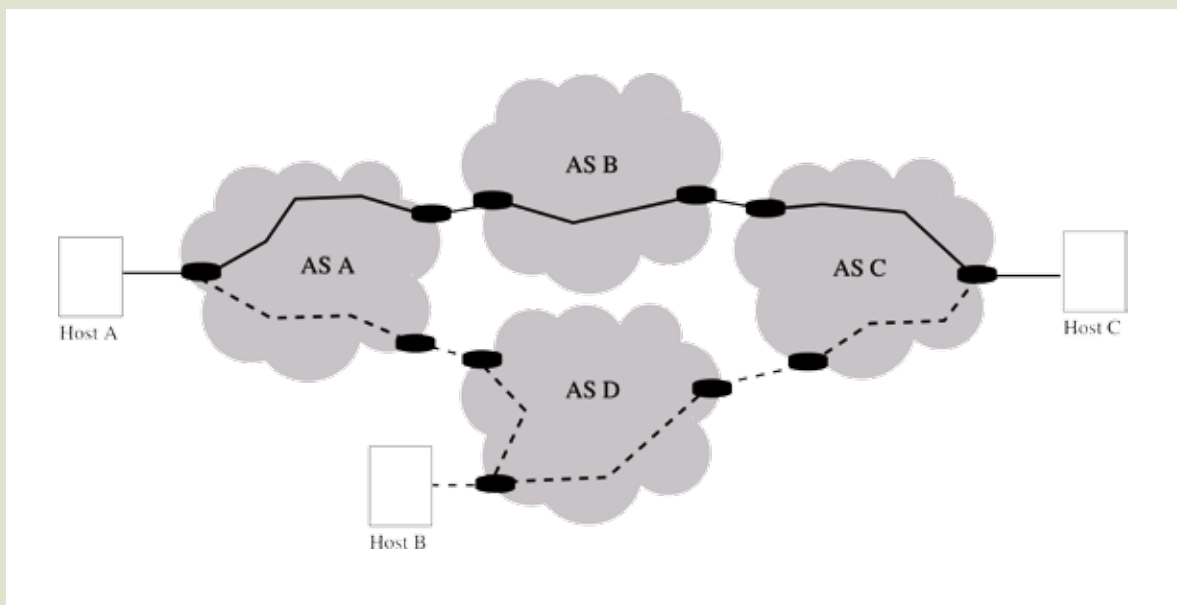


Figure 8. Overlay network.

An overlay network denoted Resilient Overlay Network (RON) is presented in [1]. The network consists of a set of 2–50 host computers that are connected to different providers. A host may act as a relay for other hosts if they can reach a server that is unavailable to other hosts or if this relaying will improve performance. The improved dependability obtained by using a RON is due to the existence of multiple paths at the interdomain level are available in the RON, and even routes that are not advertised to a given AS may in some cases be used when relaying through a node in the overlay network. In figure 8, the primary path for the connection between Host A and Host C is indicated with the solid line. The backup path, indicated with dotted line, goes via Host B. Note that the underlying AS-structure is not part of the routing information in the overlay network.

The diversity of the paths found by nodes in RON networks has been studied in [12], and it is found that the probability of finding two disjoint paths is small if the overlay nodes are chosen at random.

To improve the dependability of overlay networks such as RON, [13] suggests a method for placing the nodes so that the paths become less overlapping. This is combined with dynamic selection of backup routes via nodes that give “most disjoint” routes. Using the new strategy, many failures can be covered by going via only one node in the overlay network.

In [18], it was suggested that the access routers could forward packets after instructions from the host that is member of an overlay networks in order to reduce the load on the access links. The overlay nodes can be imagined moved further into the networks. An arrangement with one or more multi-homing routers placed in each domain is presented in [21]. The overlay routes and the data packets can be source routed in the overlay network.

Network layer approaches

These approaches try to find disjoint AS-paths by finding and using disjoint paths at the network layer.

Multihoming

Multihoming of the provider AS is currently used to have access to multiple routes. Commercial solutions to take advantage of multihoming exist. For instance, a service that monitors the connections of the user and dynamically selects the best is offered by Internap [16]. Unfortunately, multihoming does not always give

disjoint routes, so the dependability improvement is limited. There seems to be potential for methods to improve the diversity of the paths that are used, but this will require modifications to the BGP protocol.

Source routing

The IP protocol offers source routing so that a user may specify a loose or strict sequence of addresses a packet should visit before it reaches its destination. For security reasons, IP source routing is generally disabled in routers for forwarding traffic other than ICMP [14, 31]. A variant of source routing techniques could have potential to be used for improved dependability, but the security problems must be avoided.

AS-level route selection

In the literature, several authors have proposed architectures that allow stub ASes or even end users to choose the routes they want their packets to be forwarded over. The dependability might increase if the senders of the packets are able to choose from more paths than those available today. We consider AS-level route selection approaches to be different from IP source routing since the users are only allowed to choose from routes that are suggested by the ASes that will provide the transit service. To introduce AS-levels route selection, new interdomain routing protocols and architectures are needed.

Feedback based routing has recently been proposed as a network layer mechanism to improve dependability [35]. The border routers in transit networks forward information on available interdomain links and which ASes they connect. Each stub AS has an access router that calculates two disjoint routes to each destination AS based on topology information received from the routers in the transit networks. The access routers specify the path for each packet sent, and the intermediate routers forward packets according to this annotation. The quality of the connections is monitored and the best path is used as primary. For applications that demand zero down time, the data can be sent along both paths. The link state information is updated periodically with the period being at least an hour. The access routers have timers associated with each link, and if the timer expires, the routes associated with that link are attempted replaced by other routes. Other frameworks for allowing the users of stub ASes to choose the routes are Nimrod [2], NIRA [33] and BANANAS [19].

Strategy		Guaranteed protection from single failure	Service interruption time	Continuous service (1+1)	Differentiation	Comment	Selected references
Situation today	BGP today	no	long	not possible	no	slow convergence after failures	[28]
	Multihoming	no	shorter than above	possible	limited possibilities	paths not necessarily disjoint	[12]
Single AS-path	End-to-end backup	yes	short	yes	yes	need redundant inter-AS links	[29]
	Sectioned backup	yes	short	no	yes	need redundant inter-AS links	[6, 15]
Multiple AS-paths	Overlay networks	no	short	possible	yes	paths not necessarily disjoint	[1]
	Network layer	yes	short	possible	yes	need new interdomain routing architecture	[35, 33]

Table 1 Proposed strategies for improving interdomain dependability and their properties.

4.3 Comparison and evaluation

Table 1 compares the proposed strategies for improved interdomain dependability. The currently deployed BGP protocol does not offer potential for differentiated dependability, and suffers from long service interruption times. All the other strategies considered in the table have some potential for differentiation. A multihomed ISP is currently able to offer a limited form of differentiated dependability for outgoing traffic. Upon failure of the link to the ISP's primary provider AS, the link to his remaining providers could be used exclusively to send packets for customers or services with high dependability requirements. Overlay networks are also possible to establish today as they do not require any changes to the BGP protocol. However, if the overlay approach is taken, the underlying infrastructure is hidden, and it will not be possible to provide guaranteed protection from a single failure since infrastructure may be shared between any pair of paths in the overlay network.

The single-AS strategies have potential to provide routes that can handle all single failures for an end-to-end connection. The service disruption time depends on the recovery mechanisms employed, and can be short if MPLS is used. The strategies, however demand that all ASes that are part of a dependable path are upgraded with redundant inter-AS links and implement the needed functionality.

The network layer approaches using multiple AS-paths require new interdomain routing architecture to be able to be used for providing differentiated dependability.

Concluding remarks

The provision of differentiated dependability over multiple ASes in the Internet is a challenging research topic. In addition to technical challenges such as scalability, interdomain routing must also take the business relationships like information hiding and service level agreements between the ASes into account. The proposed frameworks for intradomain differentiation are not directly extensible to the interdomain level, and new frameworks are needed to cope with these challenges. Based on an evaluation on the literature on improved interdomain dependability, we have outlined two possible approaches toward interdomain differentiation. The first approach is to strengthen the interconnection between the ASes so that failures of the interdomain paths are avoided. The strengthened paths could be used to provide a service with better dependability than what is offered today to users and services with high dependability requirements. The second approach to dependability differentiation is to take advantage of the existence of multiple paths at the AS-level to maintain disjoint primary and backup paths which can be used by the users and services with high dependability requirements.

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Also in 2006, Q2S has been active within the area of new crypto primitives, in close cooperation with University Sts Cyril and Methodius, Skopje, Macedonia. Focus has been on a new public key algorithm for confidentiality and integrity based on a mathematical principle called "Multivariate Quadratic Trapdoor Functions". The underlying mathematical construction for the one-way functions are called Quasigroups, and can be described as Latin squares with seemingly random content and specifically defined arithmetic laws. The encryption algorithm is different from previously constructed public key algorithms with respect to key size and processing speed. In addition, it is particularly well suited for efficient implementation in optimized hardware. The solution is considered for patenting by the TTO at NTNU.

Cooperation projects under the EuroNgi NoE have been further developed also in 2006. The network finished its first period of operation in November 2006, but the activities are prolonged for a new project period under the new designation EuroFGI (Future Generation Internets) with practically identical participation and volume. In 2006, experts from Q2S have participated at the Plenary meeting in Würzburg, and at a PhD-course in Paris managed by University of Sussex. Significant contributions to the deliverables finished by the working groups in 2006 have also been made. There were several contributions from the centre at the EuroNGI 2006 2nd Conference on Next Generation Internet Design and Engineering which was arranged in Valencia, 2006 (<http://www.eurongi2006.upv.es/>). The NGI conference is the main conference for the network, and normally attracts more than 100 participants. The NGI conference for 2007 (<http://www.q2s.ntnu.no/eurongi2007/>) will be arranged by Q2S in Trondheim, and preparations for this event have been successfully performed.

Q2S researchers have participated at workshops held within EuroNgi. PhD candidate Anders Mykkeltveit contributed with a presentation and paper at the "Workshop on Traffic Engineering, Protection and Restoration for NGI" in Krakow, Poland in May 2006. PhD candidate Tor K. Moseng contributed with both a presentation and an accepted paper in the post-proceedings at the "Workshop on Wireless and Mobility" in Sitges, Spain in July 2006, and PhD candidates Astrid Undheim and Anne Nevin contributed with presentations at the "3rd EuroNGI Workshop on New Trends in Modelling, Quantitative Methods and Measurements" in Torino, Italy in June 2006.

The 3rd EURONGI Summer School was arranged in Laredo/Santander, Spain with the topic "NGI Network Strategy, Design and Dimensioning" in 2006. PhD candidates Erling Austreim, Tor Kjetil Moseng and Astrid Undheim from Q2S participated together with many other young people from the network.

PhD candidates from Q2S have had guest stays at several places in 2006: UCSB; University of Colorado; Fraunhofer HHI, Berlin; PEL UCD, Dublin; some of which have resulted in joint publications with researchers from the host institutions.

Lobster

UNINETT develops advanced tools for measurement of the quality of Internet traffic, for example in the EU-project Lobster. We can look at phenomena in much greater detail and get to learn more about internet traffic behaviour than with conventional network management tools. MAPI is a library that interfaces to passive measurement cards to look at high speed internet traffic in real time at rates up to gigabits per second. This library is used by different Lobster applications to search for viruses or attacks, for recognition of peer-to-peer applications, and perform flow analysis.

Geant2

In the Geant2 project, that is a collaboration between European Research Networks, we are developing perfSonar together with Internet2. Perfsonar is an inter domain measurement framework for handling problems that still are much of a research issue. Our contribution include a unique geographic network quality visualization tool (Nemo) and a multicast quality measurement tool (Ssmping) which is in international use.

Ring

Ring is an EU project to look at the next generation routing protocols that started in 2006. This is now considered an important topic both in IETF and industry for networking research to come up with scaleable solutions to Internet growth problems.

Passive measurements to aid e-VLBI

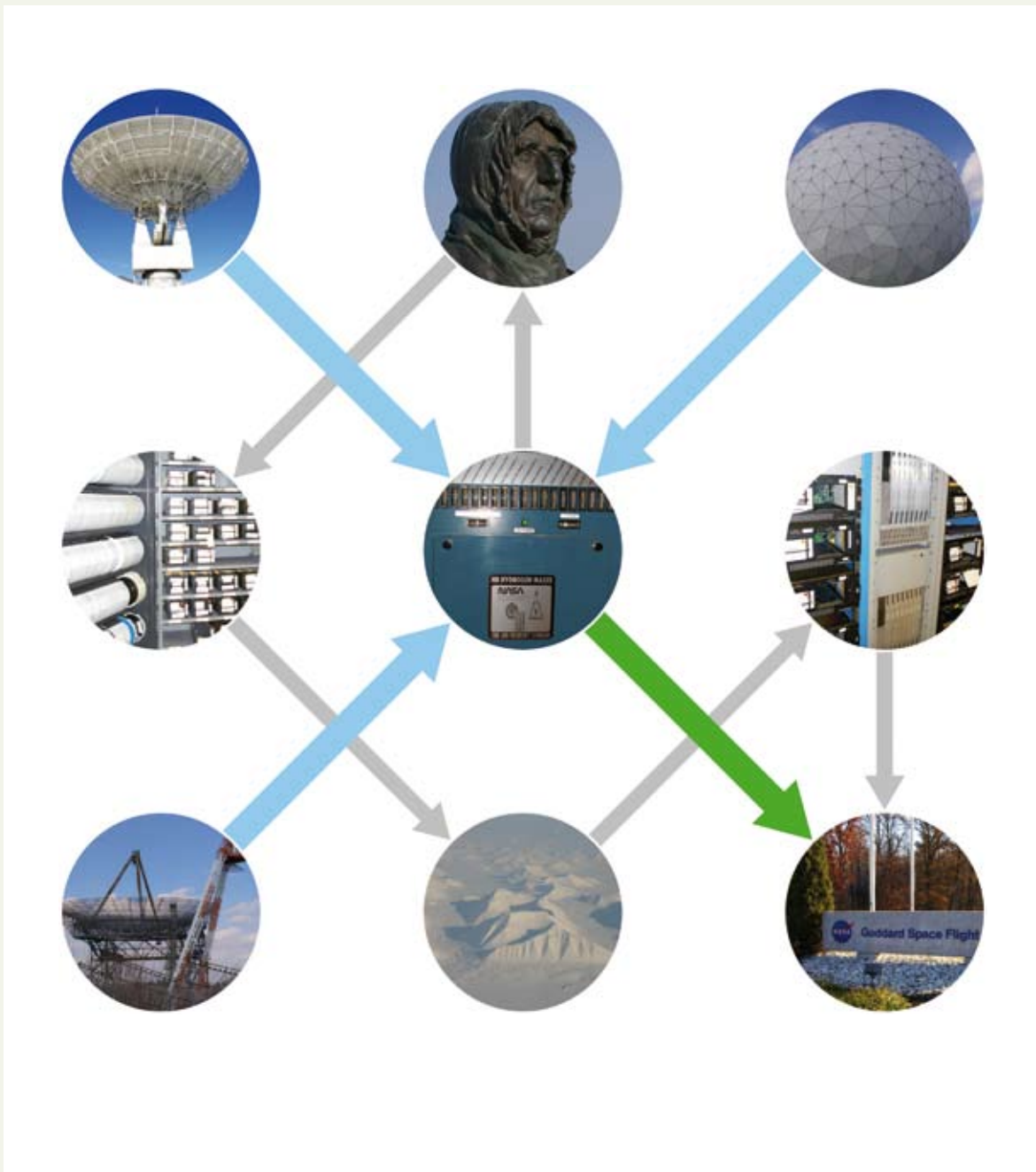
The fibre-optic cable to Svalbard in conjunction with a radio link has connected the eVLBI measurement station at Ny Ålesund to the Internet and thus made it possible to correlate the data with data from similar antennas around the globe at the MIT Haystack correlator. The

correlated data is being used for determination of tectonic plate movements, earth rotation parameters, geodesy on earth and in space among others to form a reference frame for GPS, highly accurate maps and other space related activities.

Researchers at Q2S/UNINETT has assisted NASA with passive measurement technology to improve the high performance data transport necessary to begin the task of replacing the snow-mobile and air transport of

boxes filled with hard-disks. The time to do a correlation of earth crust position measurements has now been reduced from weeks to hours, but still considerable improvements in communication capacity is needed to make correlations closer to real time.

The next steps are to build a main-land data redistribution storage center at UNINETT, researching new transport and storage protocols and ultimately to bring optical fibre all the way to Ny Ålesund.



Quality of service improved for e-VLBI research through broadband fiberoptic communication.

Q2S Statement of accounts for the year 2006

(Amount in NOK 1000)

OPERATING INCOME	Notes	Accounts
Research Council	1	4 700
NTNU		7 581
UNINETT		2 300
Telenor		1 714
EU-projects		50
Amount operating income		16 345
OPERATING COSTS		
Wages and social costs	2	15 158
Equipment and investments		831
Other operating costs		5 090
Amount operating costs		21 079
Result		-4 734
Incoming balance 2006		18 457
Result 2006		-4 734
Outgoing balance 2006		13 723

Note 1 In accordance with approved financing plan.

Note 2 The amount includes salary and social costs. Further specification, see below.

Specification for note 2

PhD candidates	Persons	Labour years 2006
Sum	18	17,0
Postdocs		
Sum	11	6,6
Professors (contributions)		
Sum	6	2,2
Visiting professors		
Sum	5	1,9
Administrative		
Sum	3	2,4

Supervision of master's theses

- Antolí, Oriol. *Intelligent layer 2 switching by CE-ants*. (Helvik, Bjarne E.; Wittner, Otto)
- Al-Karbawi, Adheed Abbas Kadhim. *Aksessikkerhet i Trådløse Trondheim*. (Knapskog, Svein J.)
- Baste, Arne Alvern. *Authentic Mobilization Orders*. (Knapskog, Svein J.)
- Christoffersen, Dag; Mauland, Bengt Jonny. *Worm Detection Using Honey pots*. (Knapskog, Svein J.; Årnes, André)
- Fylling, Torbjørn. *Kalibrering av kryssfilteret lydgiengivelse*. (Svensson, Peter)
- Gamme, Aleksander. *Nettverksbaserte Inntrengingsprevensjonssystemer*. (Knapskog, Svein J.)
- Handal, Robert. *Nærfeltsmåling av en høyttalers strålingsimpedans som grunnlag for inversfiltrering av romresponsen*. (Svensson, Peter)
- Haver, Torstein. *Security and Privacy in RFID Applications*. (Knapskog, Svein J.)
- Hellerud, Erik. *Error Concealment and Error Protection for Audio over IP Networks*. (Svensson, Peter)
- Johnsen, Lotte. *Content Distribution in Ad Hoc Networks*. (Kure, Øivind)
- Kristensveen, David. *Sikkerhet i VoIP-portnere*. (Knapskog, Svein J.)
- Marstrander, Rolf Skauen. *Adaptiv pakketapsbeskyttelse for komprimerte bilder*. (Perkis, Andrew)
- Nilsen, Ivar. *Sårbarhetsanalyse basert på CVSS*. (Knapskog, Svein J.)
- Nielsen, Marlon T.M. *Digital Kino* (Perkis, Andrew)
- Støen, Vidar. *Optimization of Band Limited Sine Sweep Measurements*. (Svensson, Peter)
- Thorvaldsen, Øystein Espelid. *Geographical Location of Internet Hosts, using a Multi-Agent System*. (Knapskog, Svein J.; Årnes, André)
- Vareide, Trude. *En MPEG-21 basert løsning for Filmweb som en 3G-tjeneste*. (Perkis, Andrew)
- Vorren, Sander Sunde. *Subjective quality evaluation of the effect of packet loss in High-Definition Video*. (Perkis, Andrew)

Refereeing activities

Professor Peder J. Emstad

Committee member of/Reviewer for:

- HET-NETs '06, Ilkley, U.K.
NGI 2006, València, Spain.

Professor Bjarne E. Helvik

Reviewer for:

- IEEE Journal on Selected Areas in Communications [JSAC], Special issue on traffic engineering for multi-layer networks.
Postproceedings of Third EuroNGI Workshop on Wireless and Mobility. for Lecture Notes in Computer Science (LNCS).

Technical Program Committee member of:

- European Dependable computing conference [EDCC'06]; Coimbra, Portugal October 10-20.
The 3rd International Workshop on Information Assurance (WIA 2007). April 11-13, 2007, New Orleans, Louisiana, USA.

Professor Svein J. Knapskog

Committee member of/Reviewer for:

- ACISP 2007: 12th Australasian Conference on Information Security and Privacy. 2-6 July 2007, Townsville, Queensland, Australia.
AISW - NetSec 2007: Australasian Information Security Workshop 2007 (Privacy Enhancing Technologies). Ballarat, Victoria, 30 January – 2 February 2007.
CCN 2006: The Third IASTED International Conference on COMMUNICATIONS AND COMPUTER NETWORKS. October 4-6, 2006, Lima, Peru.
CNIS 2006: The Third IASTED International Conference on COMMUNICATION, NETWORK, AND INFORMATION SECURITY. October 9-11, 2006, MIT Faculty Club, Cambridge, Massachusetts, USA.
IEEE Globecom: the 49th Annual IEEE GLOBECOM Technical Conference & IEEE COMMUNICATIONS EXPO. San Francisco, November 2006.
IFIP-SEC 2007: the 22nd IFIP TC-11 International Information Security Conference, Sandton Convention Centre, Sandton, South Africa, 14th – 16th May 2007.
QoP 2006: Third Workshop on Quality of Protection Workshop co-located with CCS-2007. Mon. Oct. 29 - Alexandria VA, USA.
EDCC-6: the Sixth European Dependable Computing Conference. Coimbra, Portugal, October 18 – 20, 2006.

Irma 2007: 2007 IRMA International Conference.
Conference Dates: May 19-23, 2007. *Conference Location:* Sheraton Vancouver Wall Centre Hotel Vancouver, British Columbia, Canada.

SSI 2006: 8th International Symposium on Systems and Information Security. Sao Jose dos Campos, Sao Paulo, Brazil. November 08-10, 2006.

NIK 2007: Norsk informatikkonferanse, Høgskolen i Oslo, 19. 21. 11 2007.

PhD-assessment:

Macquarie University, Sydney, Australia.

University of Bergen, Norway.

University of Oslo, Norway.

University of Western Sydney, Australia.

Academic Positions:

Professorship, Gjøvik University College.

Associate Professorship, Gjøvik University College.

Awards:

Cor Bayen Award 2006.

Professor Øivind Kure

Reviewer for:

IEEE Communication Magazine.

Professor Andrew Perkis

Reviewer for:

IEEE Transactions on Image Processing.

ETRI Technical Journal.

Technical Program Committee member of:

The 9th IFIP/IEEE International Conference on Management of Multimedia and Mobile Networks and Services.

Program Committee member of:

IEEE/ACM SITIS of the image and signal processing track.

CCNC'07- Multimedia Networking Track (2007 IEEE Consumer Communications and Networking Conference - Multimedia Networking Track).

SIGMAP2006.

Professor Peter Svensson

Reviewer for:

Acta Acustica united with Acustica.

Journal of the Acoustical Society of America.

2nd ISCA Tutorial & Research Workshop on Perceptual Quality of System, Berlin Germany 2006.

SIGGRAPH, Boston USA 2006.

Associate Editor for:

Acta Acustica united with Acustica in the field of electroacoustics.

Postdoc Crina Grosan

Reviewer for:

IEEE Transactions on Evolutionary Computation.

IEEE Transactions on Systems, Man and Cybernetics.

Evolutionary Computation (MIT Press).

Journal of Heuristics (Springer Verlag Germany).

European Journal of Operational Research (Elsevier).

Technical Program Committee member of:

Sixth International Conference on Hybrid Intelligent Systems (HIS), New Zealand, 2006.

Second Workshop on Natural Computation and Applications (NCA), in conjunction with 8th International Symposium on Symbolic and Numeric Algorithms for Scientific Computing (SYNASC), Timisoara, Romania, 2006.

First International Conference on Digital Information Management (ICDIM), Bangalore, India, December, 2006.

The First International Workshop on Intelligent Application in Product Lifecycle Management (IAPLM), China, 2006.

11th Online World Conference on Soft Computing in Industrial Applications (WSC11), World Wide Web, September 18 - October 06, 2006.

The sixth International Conference on Intelligent Systems Design and Applications (ISDA), Jinan, China, October 16-18, 2006.

Chair of:

EMODA'06: Second International Workshop on Evolutionary Multiobjective Optimization: Design and Applications (EMODA'06), in conjunction with 6th International Conference on Intelligent Systems Design and Applications, ISDA'06, Jinan, China, October 16-18, 2006.

Seminars and colloquia at Q2S

Network Survivability; Co-operation issues among AGH (Poland), Q2S and ITEM. 30. November 2006.

Lectures in the "Q2S Colloquium" series 2006

The series has been managed and organized by Otto Wittner

Gligoroski, Danilo, Q2S. *On periods of Edon-(2m,2k) Family of Stream Ciphers*. 27 January 2006.

Naumov, Valeriy, Q2S (Visiting). *Quantile estimation in large data sets and streaming data*. 10 February 2006.

Naumov, Valeriy, Q2S (Visiting). *Quantile Estimation. Part 2 – Streaming Data*. 2 March 2006.

Andresen, Steinar, ITEM NTNU. *Trådløse Trondheim som forsknings-lab*. 21 March 2006.

Gan, Qitao, Q2S. *Dependability Modelling and Analysis of Networks as Taking Routing and Traffic into Account*. 24 March 2006.

Hyttiä, Esa, Q2S. 1) *A model for TCP congestion control capturing the correlations in times between the congestion events*, 2) *On Load Balancing in a Dense Wireless Multihop Network*. 31 March 2006.

Østerbø, Olav, Telenor R&D. *Delay analysis of IEEE 802.11e EDCA and 802.11 DCF*. 28 April 2006.

Kvittem, Olav, Uninett/Q2S. *Open Telephony*. 12 May 2006.

Sztrik, János, Q2S (Visiting). *Heterogeneous Finite-Source Retrial Queues*. 9 June 2006.

Alatan, A. Aydin, Middle East Tech University. *3DTV: Scene Extraction and Representation Issues*. 15 June 2006.

Welzl, Michael, University of Innsbruck. *Grid Inter-Networking and QoS for the Grid*. 4 September 2006.

Sallhammar, Karin, Q2S. *A Game-theoretic Approach to Stochastic Security and Dependability Evaluation*. 5 September 2006.

Welzl, Michael, University of Innsbruck. *Internet Transport Tomorrow - introducing SCTP, UDP-Lite and DCCP*. 7 September 2006.

Wittner, Otto, Q2S. *Self-tuned Refresh Rate in a Swarm Intelligence Path Management System*. 8 September 2006.

Årnes, André, Q2S. *Using Hidden Markov Models to Evaluate the Risks of Intrusions*. 15 September 2006.

Mykkeltveit, Anders, and Paquereau, Laurent, Q2S. *Application of the RESTART/Splitting Technique in Object-Oriented Simulation + A Module-Based Wireless Node for NS-2*. 6 October 2006.

Murphy, Seán, Performance Engineering Lab (UCD/DCU). *An experimental analysis of VoIP over WLAN (preceded by an overview of the Performance Engineering Lab, Dublin)*. 3 November 2006.

Gan, Qitao, Q2S. 1) *A Hybrid Modelling Approach for Analyzing Service Availability*; 2) *Refined Classification of Service Unavailability for Comparison*. 17 November 2006.

Haslum, Kjetil, Q2S. *Multisensor Real-time Risk Assessment using Continuous-time Hidden Markov Models*. 24 November 2006.

Talks at conferences, seminars and meetings

T1. Helvik, Bjarne Emil. *Swarm-based routing to achieve dependable networks*. Dependability of all-IP networks; A multi-disciplinary workshop; 18.05.2006 - 19.05.2006.

T2. Johansen, Stian. *Application-level approaches to terminal Quality of Service*. WOG event "Interaction between content, terminal and network", University of Gent; 09.03.2006 - 09.03.2006.

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