PART IV

CONCLUSIONS AND FUTURE WORK

Main concepts and contributions proposed in the Thesis as well as obtained results are summarized in next Chapters. Before concluding the Thesis, lines of future work where proposed mechanisms may be extended are briefly stated.

Chapter 13

Final Conclusions

The problem known as routing inaccuracy problem arises when the information contained in the network state databases does not perfectly represent a current picture of the network. Many factors, such as non-negligible propagation delay, frequency of the updates, and hierarchical topology aggregation can affect the precision of the network state information, an immediate effect being an increase in the connection blocking probability.

This Thesis deals with mitigating the effects of routing inaccuracy in both *IP/MPLS* and *WDM* networks. The first contribution of this Thesis is the proposal of a new dynamic source QoS routing mechanism, called *BYPASS Based Routing* (*BBR*), which substantially improves global network performance in an *IP/MPLS* scenario. The most significant contribution of this mechanism is the dynamic bypass concept, which lies in applying the idea of path protection, used for fast rerouting after a failure, to the ordinary path selection routing process. Four different algorithms are inferred from the *BBR* mechanism. Two of them, *SOSP* and *OSSP*, appear when combining the *BBR* mechanism with the shortest path algorithm. The other two, *WSOSP* and *BOSP*, were designed to optimise bandwidth allocation in the routing process. Therefore, the main novelty of the proposed QoS routing mechanism is that it aims at dealing both with the network resource utilization problem (in terms of bandwidth consumption) and the routing information inaccuracy problem.

These algorithms were evaluated over both small and large networks under increasing traffic conditions, and while applying two different triggering policies, namely the Threshold and the Exponential class triggering policies. The large network used for the simulations is a common *ISP* network used in many QoS routing studies in order to provide results with realism. Under these conditions, the *BBR* mechanism was compared with the *SP* algorithm (non-QoS routing), the *WSP* algorithm (QoS routing), and the *SSP* algorithm (an existing solution for the routing inaccuracy problem). As a result it was found that the lowest blocking probability was obtained when applying the *BOSP* algorithm, which under worst conditions achieves a blocking probability reduction of 8.3% compared to the *SSP* algorithm, followed by the *SOSP* algorithm with a reduction of 6 % also compared to the *SSP* algorithm. The *BBR* mechanism is also extended with the *BYPASS Discovery Process* (*BDP*). The *BDP* is introduced to improve the *BBR* applicability by allowing *bypass-paths* to be computed in most network topologies. Obtained results show a blocking probability reduction when including the *BDP* in the *BBR* mechanism.

The main benefit obtained when applying the *BBR* mechanism is the reduction in the bandwidth blocking. However, as dynamic rerouting along pre-computed *bypass-paths* is the solution introduced by the dynamic bypass concept, the obtained reduction depends on the number of *bypass-paths* that can be computed per route. Several simulations are performed to show the impact on the blocking probability as a function of the number of computed *bypass-paths* per route. Results exhibit that larger blocking reduction is obtained when *bypass-paths* are not limited. However the cost introduced is not affordable. A trade-off exists between the bandwidth blocking reduction and the cost. A reasonable cost is reached when three *bypass-paths* per route are allowed. It is also analysed a different policy to reduce the cost. Unlike the above mentioned policy where the cost is reduced by limiting the number of computed *bypass-paths* per route to a fixed value, the new policy limits the cost by defining the *n_bp* value as a function of the network load, so-called network load dependent. After comparing both policies we can conclude that while a significant reduction in the cost of about 8.6% is achieved when *n_bp* is dependent on the network load, the use of this policy does not involves a significant decrease in the obtained bandwidth blocking when using the other policy.

A second contribution of this work is to apply the *BBR* mechanism suggested for *IP/MPLS* networks to *WDM* networks. The *BYPASS Based Optical Routing* (*BBOR*) mechanism, also based on the dynamic bypass concept, has been proposed. *BBOR* consists of two main components, a triggering policy adapted to optical networks and two routing algorithms, *ALG1* and *ALG2*. The evaluation of *ALG1* and *ALG2* was done by applying them to a wavelength-selective network and comparing their performance with the *First-Fit* heuristic. The simulation results showed a significant reduction in the number of update messages (79.65%) achieved when applying the triggering policy defined in the *BBOR* mechanism. Moreover, analysing the worst case (i.e., under conditions of high volume traffic and routing inaccuracy), both *ALG1* and *ALG2* achieve a similar reduction of about 16% in the connection blocking probability compared to the *First Fit* heuristic.

After that the *BBOR* is applied to networks with conversion capabilities. It is well known that although wavelength converters are currently very expensive, they substantially improve global network performance, such as reducing the connection blocking. This solution could be referred as “hardware solution”. *ALG3* is a new algorithm inferred from the *BBOR* mechanism which computes lightpaths according to a new defined factor which represents a balance between the number of links where the selected wavelength potentially might be unavoidable and the real congestion. *ALG3* achieves a lower connection blocking when is applied to networks with conversion capabilities.

Moreover, *ALG3* has also been applied to networks without conversion capabilities. Obtained results are compared to those obtained when applying the shortest path algorithm to a network with sparse and limited conversion. After carefully analysing these results, the *BBOR* mechanism can be though as a “software solution” to reduce the connection blocking without requiring an important investment in wavelength converters.

Chapter 14

Future Work

The work and the contributions proposed in this Thesis may be extended given rise to several lines of future work. As stated before, this Thesis proposes QoS routing mechanisms which can be applied to both *IP/MPLS* and *WDM* networks. In these different scenarios there are various ways in which this work may be continued.

An initial extension of the already proposed mechanisms concerns to *IP/MPLS* networks. The network scenario considered so far is based on a flat topology. This network scenario may be modified considered hierarchical routing. In this case, the routing inaccuracy problem is motivated by both the existence of triggering policies and the state aggregation process performed in any hierarchical structure. An analysis of the *BBR* behaviour in this hierarchical network scenario may be performed. Depending on obtained results, new algorithms must be generated.

Up to now, the mechanisms proposed to address the routing inaccuracy problem tackle independently the problem. In fact the *BBR* is applied in *IP/MPLS* networks and the *BBOR* in *WDM* networks. However both technologies can interoperate in such a way that routing may be simultaneously performed. The implications of this interlayer operation on the routing inaccuracy problem must be carefully analyzed.

All simulation results obtained so far for *WDM* networks focus on reducing the blocking probability ratio. The main goal is to apply a certain wavelength assignment heuristic and to find the reduction obtained in the blocking probability when considering the routing inaccuracy problem. Another future work is related to network dimensioning. In this new scenario, the input parameter is a certain degree of service which is required by the incoming connections. The main objective is to dimension both the number of wavelength converters that must be added to the network and the degree of conversion of each converter, to meet the required degree of service according to traffic conditions.

Finally, the hierarchical network structure can be also applied to *WDM* networks. The impact of different aggregation schemes in the routing inaccuracy and the blocking probability must be analyzed. New routing algorithms taken into account the inaccuracy introduced by the state aggregation process and the different aggregation schemes to be proposed must be sought.

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APPENDIX A:

List of Publications and Projects

Main publications

1) X.Masip-Bruin, S.Sànchez-López, J.Solé-Pareta, J.Domingo-Pascual,, "*An Alternative Path Fast Rerouting in MPLS*", in Proceedings of ISCIS XV, pp.304-313, Istambul, Turkey, October 2000.

2) X.Masip-Bruin, R.Muñoz, S.Sànchez-López, J.Solé-Pareta, J.Domingo-Pascual, G.Junyent, "*Mecanismo de Encaminamiento Dinámico en Redes ASON*", XII Jornadas Telecom I+D, Barcelona, Spain, November 2002.

3) X.Masip-Bruin, R.Muñoz, S.Sànchez-López, J.Solé-Pareta, J.Domingo-Pascual, G.Junyent, "*An Adaptive Routing Mechanism for Reducing the Routing Inaccuracy Effects in an ASON*", in Proceedings of 7th IFIP Working Conference on Optical Network Design & Modelling, pp. 333-349, Budapest, Hungary, Feb. 2003.

4) X.Masip-Bruin, S.Sànchez-López, J.Solé-Pareta, J.Domingo-Pascual,, "*A QoS Routing Mechanism for Reducing the Routing Inaccuracy Effects*", in Proceedings of 2nd International Workshop on QoS in Multiservice IP Networks, QoS-IP, pp.90-102, Milan, Italy, February 2003.

5) X.Masip-Bruin, S.Sànchez-López, J.Solé-Pareta, J.Domingo-Pascual, "*A Mechanism to Reduce the Routing Information Inaccuracy Effects: Application to MPLS*", Workshop on MPLS, Girona, March 2003.

6) X.Masip-Bruin, S.Sànchez-López, J.Solé-Pareta, J.Domingo-Pascual,, "*QoS Routing Algorithms Under Inaccurate Routing Information for Bandwidth Constrained Applications*", in Proceedings of IEEE International Communications Conference, ICC 2003, Anchorage, Alaska, May 2003.

7) J.Solé-Pareta, D.Careglio, X.Masip-Bruin, S.Sanchez-López and S.Spadaro, "*Some Open Issues in the Definition of a Control Plane for Optical Networks*", Invited paper submitted to IEEE 5th International Conference on Transparent Optical Networks, ICTON 2003, Warsaw, Poland, June 2003.

8) De Maesschalck, D. Colle, B. Puype, Q. Yan, M. Pickavet, P. Demeester, S.Sánchez-López, X.Masip-Bruin, J. Solé-Pareta, et al, "*Circuit/Wavelength Switching and Routing*", in Proceedings of 7th. International Conference on Telecommunications, ConTEL 2003, Zagreb, Croatia, June, 2003.

9) P. Van Mieghem, F.A. Kuipers, T. Korkmaz, M. Krunz, M. Curado, E. Monteiro, X. Masip-Bruin, J. Solé-Pareta, S. Sànchez-López, "Quality of Service Routing", Chapter 2 of book "QUALITY OF FUTURE INTERNET SERVICES: COST 263 FINAL REPORT", Ed. Springer-Verlag, 2003, ISSN: 0302-9743 (in press), October 2003

10) X. Masip-Bruin, S. Sànchez-López, J. Solé-Pareta, et al. Contribution to Chapter 3 on "*Design optimized reliable WDM networks*" of COST 266 Final Report, October, 2003.

11) X. Masip-Bruin, S. Sànchez-López, J. Solé-Pareta, J. Domingo-Pascual, D. Colle, "*Routing and Wavelength Assignment under Inaccurate Routing Information in Networks with Sparse and Limited Wavelength Conversions*", in Proceedings of Global Communications Conference, IEEE GLOBECOM 2003, San Francisco, CA, December 2003.

Other publications

1) S.Sànchez-López, X.Masip-Bruin, J.Domingo-Pascual, "*Protocolo RSVP: evolución y experiencias*", Jornadas Técnicas RedIRIS 98, Noviembre 1998, Barcelona, Spain.
2) S.Sànchez-López, X.Masip-Bruin, J. Domingo-Pascual, J. Solé-Pareta, "*A Solution for Integrating MPLS over ATM*", in Proceedings of ISCIS XV, Istambul, Turkey, October 2000.
3) S.Sànchez-López, X.Masip-Bruin, J.Domingo-Pascual, J.Solé-Pareta, J.López, "*A Path Establishment Approach in an MPLS-ATM Integrated Environment*", in Proceedings of IEEE GLOBECOM, S.Antonio, Texas, Nov. 2001.
4) S.Sànchez-López, X.Masip-Bruin, J.Solé-Pareta, J.Domingo-Pascual, "*Providing QoS in MPLS-ATM Integrated Environments*", in Proceedings of QofIS'02, Zürich, Switzerland, October 2002.
5) S.Sànchez-López, X.Masip-Bruin, J.Solé-Pareta, J.Domingo-Pascual, "*PONNI: A Routing Information Exchange Protocol for ASON*", in Proceedings of Eurescom Summit 2002, Heidelberg, Germany, October 2002.

Projects

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APPENDIX B:

The ns/2 Simulator

The ns/2 simulator is a discrete event simulator targeted at networking research. The ns/2 provides substantial support for simulation of *TCP*, routing and multicast protocols over wired and wireless networks. Even though it began as a variant of the *REAL network simulator* in 1989, it is not a polished and finished product, but the result of an on-going effort of research and development. In fact, the ns/2 is still being improved and modified by most users around the world. Currently, there are several web pages where information about bugs, updated versions and comments can be found.

The ns/2 was the first option when locking for a network simulator where network performance could be evaluated. There are two main reasons supporting this decision: it is free (that is a good reason), and it provides users with completely freedom to modify any network parameter, from network topology to traffic characteristics and routing mechanisms. Therefore, the ns/2 is very attractive because it allows us to include in the network mechanisms developed in this Thesis and to evaluate their performance.

The ns/2 simulator has been properly modified to support *MPLS* capabilities, to implement new routing mechanisms and finally to represent a *WDM* network.

Concerning the *MPLS* module only required features have been developed. Basically these are the following:

- Label generation
- Label distribution
- Explicit LSP set-up
- Label space
- Label control
- Signalling mechanisms
- Label Distribution Protocol
- Label allocation

As far as the routing mechanisms concerns, all the routing algorithms inferred from the *BBR* mechanism have been implemented. Therefore, the following routing algorithms are included:

- *SP*: Shortest Path
- *WSP*: Widest-Shortest Path
- *SSP*: Shortest-Safest Path
- *SOSP*: Shortest-Obstruct-Sensitive Path
- *OSSP*: Obstruct-Sensitive-Shortest Path
- *WSOSP*: Widest-Shortest-Obstruct-Sensitive Path
- *BOSP*: Balance-Obstruct-Sensitive Path
- *BOSP/BDP*: *BOSP* along with the *BYPASS Discovery Process*
  - Limiting by a fixed value the number of computed *bypass-paths* per route
  - Limiting the number of computed *bypass-paths* depending on the network load

Finally, the simulator has been extended with optical capabilities. This really means that some features of *WDM* networks may be simulated when including our modifications. Basically, the simulator has been provided with the following:

- Selects more than one feasible shortest route
- Modifies the network state databases and the update messages to include optical information, such as number of fibres, number of wavelengths, and wavelength availability
- Includes wavelength conversion capabilities. Sparse and limited wavelength conversion is allowed.

The *BBOR* mechanism is developed in this optical network scenario, therefore the following routing algorithms are implemented in the simulator:

- SP + ALG1: Algorithm 1
- SP + ALG2: Algorithm2
- SP + ALG3: Algorithm 3
- SP + First-Fit: First-Fit