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CHAPTER 6

6.1 Summary

As noted in Chapter 1, CAC, flow control and sewice-rate control are three principal technical problems in BISDN. In Chapter 2, due to the complexity of the control problems in BISDN we proposed a hierarchically organised control structure.
Additionally, due to the nonstationary behaviour of the network, different (dynamic) modelling techniques are proposed as being essential. Also for the efficient control of BISDN it is proposed that the (dynamic) tradeoff between service-rate, buffer-space, cell-delay and cell-loss cannot be ignored.

The primary focus of this thesis has been in the development of new dynamic CAC, flow control and service-rate control structures and methods, which can (possibly) form a part of an overall hierarchically organised BISDN control solution. In this thesis we offer new design and analysis techniques, which are applicable to both the stationary and the nonstationary behaviour of BISDN systems. The **tradeoff** between service-rate, buffer-space, cell-delay and cell-loss has been incorporated in the problem formulation.

In chapter **3** we have demonstrated that using the general tools of adaptive control, featuring on-line system identification techniques, robust, effective and efficient control can be implemented. It offers guaranteed **QoS** together with high utilisation of link capacity. In particular, we integrate the formulation of the **CAC** and flow control problems. Due to our novel control formulation the network efficiency can be maintained at high levels (theoretically at unity utilisation) yet the offered **QoS** can be regulated to defined target values. Since ACFC is implemented locally it is insensitive to propagation delays between nodes along its path. Using analysis and simulation its performance has been investigated. Bounds on the operating conditions are derived and using simulation we have shown the adaptability, robustness and increased efficiency of

the scheme. Additionally, this scheme is dependent on only two broad traffic classifications: the uncontrollable and controllable groups of traffic. It is independent of the arrival process model, and it does not require any user declared parameters other than the peak rate for connections identified as uncontrollable.

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In chapter 4 using multilevel optimal control theory, decentralised coordinated solutions are derived. These are based on a novel service-rate control scheme that uses feedback **from** the network queues. The derived solution is not sensitive to the propagation delays. Its performance has been investigated using simulation techniques.

Finally in chapter 5 the demonstration of a hierarchically structured overall solution is shown for the control of service-rate, in which the solutions at the various levels of the hierarchy are integrated. Four levels are formulated: multiobjective VPAM; VPOSU; VPC; and LSP.

6.2 Contributions of this work

In this section we list the primary contributions presented in this thesis in the order of their appearance.

- In Chapter 2
 - we present arguments to support the assertions that:
 - feedback control is feasible, despite the propagation delays, as long as it is constrained to lie within the control horizon (for example by appropriate vertical and horizontal decompositions);
 - for the overall control of BISDN, a hierarchically organised control structure featuring a vertical as well as a horizontal decomposition is essential;
 - that a number of different dynamic modelling techniques must be employed;
 - and that the dynamic **tradeoff** between service-rate, buffer-space, cell-delay and cell-loss must be exploited.
 - We also present a new view of hierarchical structure based on the system behaviour in both time and space.
- In chapter 3
 - we make use of adaptive feedback and adaptive feedforward control methodologies, to solve the combined connection admission control and flow control problem.
 - we introduce a novel control concept, based on only two groups of traffic:
 - the controllable traffic, and

• the uncontrollable traffic.

Based on these two groups of **traffic** we achieve:

- network controllability by appropriate formulation of the CAC policy.
- we achieve high utilisation of resources and yet maintain the quality of service at prescribed (reference) values. Thus we achieve:
 - low cell-loss and (for the group of uncontrollable traffic) low cell-delay, and low cell-delay-variation (maintained at all times by regulating the QoS);
 - high efficiency (theoretically unity utilisation).
- We have proven analytically, using certain assumptions, that in the long term:
 - the regulator is stable and that it converges to zero regulation error;
 - the utilisation is equal to unity;
 - the controlled network is stable (as long as the uncontrollable traffic remains bounded, by the connection admission control scheme, below the link service-rate);
 - that guaranteed (worst case) bounds on the quality of service can be offered by the network to the user (worst case delay only applies to the uncontrollable traffic).
- Using simulation we have supported the above mentioned proofs and demonstrated the following features:
 - efficiency (a utilisation of 0.89 was demonstrated for a particular set of values for the reference and the expected overflow constant, a 48% improvement over a peak rate allocation scheme. Note that this can be improved **further** by setting the reference higher or the expected overflow constant at a lower value);
 - robustness to unforeseen traffic;
 - maintenance of the **QoS** close to the reference values;
 - ability to influence local behaviour.
- the only traffic descriptor required **from** the user is that of the peak rate of the uncontrollable traffic. (This can be compared with some of the schemes

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proposed in the literature that require a full and accurate traffic descriptor in advance of the call connection to the network; even with an assumed accurate model these schemes mainly aim at cell-loss minimisation, without the simultaneous achievement of high network efficiency).

- only two simple **traffic** classifications (the controllable and uncontrollable groups) are required, irrespective of the detailed behaviour of the connections.
- In Chapter 4:
 - a novel scheme for the dynamic control of service-rate based on feedback from the network queues is proposed.
 - a unified dynamic fluid flow equation to describe the VP is presented.
 - two illustrative examples for the feedback control of service-rate at the VP level are formulated:
 - a nonlinear optimal multilevel implementation, that features a coordinated decentralised solution;
 - a single level implementation that turns out to be computationally complex. Therefore for the single level,
 - the costate equilibrium solution was also derived (using simulation we demonstrate that the costates do attain equilibrium and that this is close to the optimal solution).
 - a discussion of the implementation complexity of the derived optimal policies is included.
 - implementable solutions for the derived optimal policies are considered.
 - extensions are given for previous published works, on the optimal control of nonlinear systems, to the general case of large-scale nonlinear time-delayed systems.
 - we present simulative performance evaluation of the schemes. We have shown that:
 - a Control System Type Simulation (CSTS) closely resembles a Discrete Event Nonstationary Simulation (DENS);
 - the local behaviour of the LUs can be influenced via changes in the references and/or the weighting coefficients that appear in the objective function;

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- the interaction between the nodes spanned by a VP becomes more pronounced as the service-rate rate available at a link becomes scarce (as for example during a high load situation);
- the effect of the interactions of the nodes along a VP can be minimised by the use of coordinated decentralised LUs;
- there is a **tradeoff** between buffer-space and service-rate.
- In Chapter 5:
 - we demonstrate the derivation of a particular solution for the control of servicerate using a hierarchical structure. In particular, we:
 - decomposed the system both vertically and horizontally to provide local coordinated decentralised solutions at the lower levels of the hierarchy and more global solutions operating at slower time scales at the higher levels.
 - For the case of **VPAM**, the highest level of the presented hierarchy, we extend published results to the case of a multiobjective formulation.
 - At the lowest levels of the hierarchy, we proposed LSP, a novel link server protocol derived **from** heuristic arguments.
 - At the intermediate level we use VPC, the dynamic service-rate control scheme described above.
 - In order to demonstrate the flexibility and adaptability of the hierarchical structure an additional level VPOSU is also formulated.
 - we extend **VPAM** to the case of multiple objectives, so that it can deal with issues of fairness, and multiple (possibly) conflicting objectives. We have shown through a simple example that
 - the solution set of the multiobjective formulation contains the particular solutions of the sum and product forms of single objective formulations.

6.3. Future extensions

The control structures and techniques proposed in the thesis appear very attractive for telecommunication problems, and they generate a large number of open questions. This

thesis suggests these open questions are worth pursuing. We firstly present some general extensions and then specific extensions for the works presented in Chapters 3, 4 and 5.

General future extensions

- The use of the general tools of adaptive control and non-linear optimal multilevel control have been demonstrated in this thesis for the CAC, flow control and service-rate control problems. Extension to other telecommunication problems is strongly recommended.
- The transmission-rate (Chapter 3) and the service-rate (Chapter 4) control schemes have been investigated independently (their integration is briefly discussed in section 3.3.1.4). A formal investigation of the interactions and possible integration of these two schemes is recommended. Alternatively these two schemes can be seen as competing approaches for the control of BISDN and thus a comparative study may be useful.

The provision of an overall coordination scheme that uses a combination of changing (by the higher level supervisor) the reference values as well as the weights in the objective functions of the local units . This combination may provide a more adaptable as well as flexible overall system. The changes on the weights can be made adaptively based on the overall state of the network. For example in cases of low network loading the weights on capacity may be relaxed, thus giving local units more freedom to deviate from the higher level directives (the reference values). Additionally, more selectivity may be introduced for different classes of traffic, depending on their tolerance of **cell**-delay **and/or** cell-loss. Some options for the updating of the weights that are worthy of **further** investigation are:

- updating of the weights based on a heuristic (possibly semiautomatic, or even purely manual) updating of the coordination variables, say from knowledge gathered from statistical data.
- introduction of a market based mechanism (see for example [242]), and letting the internal prices set the coordination variables (the weights in the objective function of the local units). Shadow prices may provide a basis for the price adjustment mechanism, however we do not recommend sole reliance on shadow prices [243].

These options must be integrated with the overall scheme that updates the reference values.

- The relationship between time scales and decompositions has not been explored. Their formal study is recommended.
- A formal study of the timing requirements and information flows of the different levels of the hierarchy, as well as their cost is an open question well worthy of investigation.
- Due to the high speed of the network, dynamic routing is a higher level (than the cell level) function. It is of interest to investigate possible timescales and the interaction of routing with the other schemes described in this thesis.

Future extensions specifically for the CAC and flow control problem

- A comparison of the proposed (SISO-Single Input Single Output) implemenation with a multivariable (SIMO-Single Input Multiple Output) (for example option 1 proposed in section 3.2.2, page 35) or MIMO (Multiple Input Multiple Output) (for example an additional feedback signal from the queue length can prove useful) implementation is worthy of investigation.
- An adaptive multilevel **[244]** implementation. For example multiple local control units (one for each controllable source) can be used to individually control the transmission-rate of the controllable connections (for example option 1 proposed in section 3.2.2, page 35). These local units can be located at the customer premises.
- Appropriate jacketing software to prevent the regulator from reacting to unforeseen circumstances is an essential ingredient in any practical implementation. Use of fuzzy logic, or expert systems methodologies, to assist in this area, is worthy of investigation.

Future extensions specifically for the service-rate control problem

- The estimation of the ensemble averages may prove challenging. As already pointed out, **Warfield** et **al** [98] have presented a simple, recursive, real time estimator of the arrival rate. Its incorporation with the service-rate control algorithms is worthy of further investigation.
- An optimal multilevel implementation for the control of service-rate is proposed in chapter 4. It is of interest to investigate the use of adaptive (multilevel) control theory. In particular the use of continuous time methods (for example continuous time GPC [245], [246], or continuous time robust adaptive LQ control [247]), suitably extended to a multilevel implementation, may prove of value.

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- The adaptive solution of the nonlinear optimal control problem, including the TPBV problem, may provide computationally attractive (implementable) solutions.
- Fuzzy optimal control [248] appears promising, and its incorporation into this scheme to allow for easier algorithmic solutions, is also worthy of investigation.
- The dynamic creation and deletion of VPs creating a reconfigurable network, see for example [249], and the interaction with the allocation of service-rate to VPs may be of interest.
- The solution of the combined service-rate and buffer-space control problem may provide for more efficient use of the resources.

Future extensions specifically for the hierarchically organised control of cell-service-rate

- The use of feedback from lower levels to the higher levels of the hierarchy (VPAM is currently open loop based) can (possibly) increase the overall robustness of the scheme; see for example [31].
- The extension of the multiobjective VPAM to include other objectives, as for example the maximisation of revenue, **minimisation** of total network call loss and the **minimisation** of total network delay, will offer better compromise solutions (say between the customers and the network operator).
- The derivation of an optimal Link Server Protocol, and its comparison with the proposed heuristic **LSP** strategy is worthy of **further** investigation.

6.4 Concluding remark

In this thesis adaptive control theory and multilevel optimal control theory have been **successfully** employed. Their suitability for BISDN control has been demonstrated through specific problem formulations. We offer an integrated structured approach to the control of BISDN that has the essential features of implementability, efficiency, effectiveness and robustness.

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