ADAPTIVE WIENER FILTERS IN CONTROL AND SIGNAL PROCESSING: A PROJECT SUMMARY

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1 Introduction: what are our aims?

In the project, work has been carried out on problems spanning the fields of Signal processing, Communications, and Control. A guiding principle has been to formulate general problems, originating from relevant applications. Here *equalization of fading mobile radio channels* has served as a main source of inspiration, and also a useful application for testing new ideas. The aim is, however, to develop general tools and methods useful for a large range of problems.

Very central in our work is the desire to obtain explicit solutions and to gain engineering insight. As a means to accomplish that, the Polynomial Systems framework has been used. It describes linear dynamic systems in input–output form, and has been useful in our study of general IIR-filter structures, implicit adaptive schemes, probabilistic descriptions of model errors, and utilization of *a priori* information. Our long term goal is to provide a general model–based design concept, for solving a variety of problems in Signal Processing, Communications and Control. The publication of the book chapters [B2], [B3] and [B4] are steps towards this goal.

A short summary of the main activities within the project will be given next. For a more complete picture, see the list of publications.

2 Multivariable estimation and control

The initial steps in this project were taken towards linear recursive equalizers and decison feedback equalization, [P1]–[P3]. During that work, in particular while struggling with the decision feedback equalization problem in [P3], we felt that no really simple and systematic method was available for solving (multivariable) estimation and control problems formulated in input–output form. In [P5] and [P8], such a metod was suggested. The simplicity of this method has proved very useful in solving a variety of estimation and control problems, see e.g. [B2]–[B4]. The approach has also been generalized to cope with robust estimation and control problems [P9],[P11],[P13],[C5]–[C7],[N6]. Relations between this method, the classical Wiener approach, and the inner–outer factorization approach were clarified in [B3] and [B4]. See also [P5],[P12].

A duality between deconvolution and feedforward control problems was demonstrated in [P10] and utilized in [P9],[P13].

3 Adaptive equalization

We advocate the use of *indirect* adaptive schemes, where a model of the system is adjusted, and the filter/estimator/receiver is modified accordingly. They offer several advantages as compared to direct methods, in which the filter coefficients are adapted by e.g. LMS.

For example, the number of parameters in the channel estimator is often smaller than the required number of equalizer parameters. This is particularly evident when a large smooting lag is used. In an indirect scheme, the equalizer parameters do not need to be updated at every sample. The updating can be tailored to the variability of the channel coefficients. For severe time variations, as in e.g. a Rayleigh fading mobil radio environment, the channel parameters vary more smoothly than the equalizer parameters do. This makes tracking of channel parameters easier.

Also, time variations of the channel coefficients can be modelled explicitely, e.g. by means of nonlinear functions. If feasible, this would be much harder to accomplish for the equalizer parameters directly. Furthermore, there might exist several local minima to the loss function used in the direct schemes.

For fading mobile radio channels, both *deterministic and stochastic modelling* of the channel coefficients have proved to be very useful. In a Rayleigh fading environment, the time–variant channel coefficients behave approximately as sinusoids, with frequency proportional to the speed of the mobile. An adequate model would thus be a first order Fourier series expansion, see [N4] and [B1]. Such *a priori* information can also be built into a Kalman filter, see [N7] and [B1]. As a bonus, several methods for estimating the speed of the mobile have been obtained.

Based on an estimated channel model, a Viterbi detector or DFE could be used to estimate the transmitted sequence. When the approaches described above were evaluated on a channel model utilized in the North American mobile radio standard, they performed better than both direct and indirect schemes based on ordinary RLS–tracking. See [B1], [N7] and [C8].

4 Robust estimation and control

Irrespective of how models in signal processing, communications and control are obtained, they are imprefect. This is so, for example, in mobile radio applications, where standards often impose constraints on achievable model quality. To obtain filters and controllers which are insensitive to spectral uncertainties, we suggest a robust design philosophy based on *probabilistic descriptions of model errors.* A guiding principle is that large but unlikely model uncertainties should be credited, but they are not allowed to dominate the design. Therefore, we minimize the mean square estimation error (MSE), *averaged* with respect to the possible model errors. In this way, conservative filters are avoided. See Figure 1.

As error models we use additive transfer functions, having stochastic numerators and fixed denominators. Estimates of the size of model errors (coefficient covariance matrices) are easy to obtain in digital communications applications. Results have been obtained for linear recursive equalizers, decision feedback equalizers, state estimation, and feedforward control. Somewhat surprisingly, the resulting design equations become almost as simple as in the nominal case. For details, see [P9],[P13],[C5]–[C7] and [N6]. When used within the GSM standard, robust DFE's far outperform DFE's based on nominal models. See [C7] and our poster at this conference.

Figure 1. Sensitivity of filtering result based on channel model $B(z^{-1}) = 0.5z^{-1} + b1z^{-2}$, with $b1 = -0.4$ nominal, and standard deviation 0.15. The MSE of a nominal filter (solid) is sensitive. Robust filtering, as in [P9], brings insensitivity at the price of only a small MSE–increase in the nominal case. Compare to the lower bound (dotted), achievable with knowledge of the true parameter value.

4 Summary of results

We have participated in the Digital Communications program for the full 5.5–year period, but at decreasing funding levels. Let us try to summarize the total output of the project.

- One Licenciate thesis [B1] by Lars Lindbom.
- Three book chapters [B2]–[B4] summarizing many results, but also containing novel work.
- The papers [P1]–[P12], of which many are full papers in leading international journals, as well as the conference contributions [C1]–[C9].
- One patent application [P14].

In addition, several more journal papers are in preparation. One person (Kenth Öhrn), who has been partially supported by the project, will submit his licenciate thesis this year. Lars Lindbom will complete his doctorate thesis in 1994.

Several of the results have direct industrial relevance. We would, in particular, like to mention the "KLMS" algorithm by Lars Lindbom, for tracking fading mobile radio channels [B1],[C8],[N7]. By utilizing a priori information, it manages to achieve close to optimal (=kalman predictor) performance, at only twice the LMS computational load. See Figure 2 below. This unequalled combination of high performance and low complexity makes it attractive for use in the North American Digital mobile radio system. A patent application [P14] has been filed.

A lasting legacy of the project is that we have built up a considerable expertise in digital communication within our group, which was formerly focused on system identification and automatic control. Finally, working on a project which has generated such a flow of ideas and results has been great fun for all of us.

Figure 2. Performance of an adaptive Viterbi receiver, based on the novel KLMS algorithm (dashed). Compare to the ideal Kalman predictor (dash–dotted), RLS tracking with optimal $\lambda = 0.7$ (dotted) and a known channel (solid) For details, see [B1] or [C8]. USA system specifications assumed.

LIST OF PUBLICATIONS

Licenciate thesis and book chapters:

B1. Lindbom L. (1992)
Adaptive equalization for fading mobile radio channels. Licenciate Thesis, Department of Technology, Uppsala University. (120 pages.)

B2. Sternad M. and A. Ahlén (1993)
LQ–controller design and selftuning control. In Ed's K.J. Hunt: *Polynomial Methods in Optimal Control and Filtering.* Peter Peregrinus Ltd, Control Engineering Series. (36 pages.)

B3. Ahlén A. and M. Sternad (1993)
Optimal filtering problems.
Same volume as **B2**. (40 pages.)

B4. Ahlén A. and M. Sternad (1994)
Derivation and design of Wiener filters using polynomial equations. In Ed's C.T. Leondes: *Academic Press Theme Volumes on Digital Signal Processing Techniques and Applications*, Academic Press. (66 pages.)

Journal papers and patent application:

P1. Ahlén A. and M. Sternad (1989)
Optimal deconvolution based on polynomial methods. *IEEE Trans. on Acoust., Speech and Signal Proc.*, vol ASSP–37, pp 217–226.

P2. Ahlén A. (1990)
Identifiability of the deconvolution problem. *Automatica*, vol 26, pp 177–181.

P3. Sternad M. and A. Ahlén (1990)
The structure and design of realizable decision feedback equalizers for IIR channels with coloured noise. *IEEE Trans. on Information Theory*, vol IT-36, pp 848–858.

P4. Carlsson B., A. Ahlén and M. Sternad (1991)
Optimal differentiation based on stochastic signal models. *IEEE Trans. on Signal Processing*, vol SP-39, pp 341–353.

P5. Ahlén A. and Sternad M. (1991)
Wiener filter design using polynomial equations. *IEEE Trans. on Signal Processing*, vol SP-39, pp 2387–2399.

P6. Sternad M. (1991)
Use of disturbance measurement feedforward in LQG self–tuners. *Int. J. Control*, vol 53, pp 579–596.

P7. Carlsson B. M. Sternad and A. Ahlén (1992)
Digital differention of noisy data measured through a dynamic system. *IEEE Trans. on Signal Processing*, vol 40, pp 218–221.

P8. Sternad M. and A. Ahlén (1993)
A novel derivation methodology for polynomial–LQ controller design. *IEEE Trans. on Automatic Control*, vol 38, pp 116–121.

P9. Sternad M. and A. Ahlén (1993)
Robust filtering and feedforward control based on probabilistic descriptions of model errors. *Automatica*, vol 29, no 3.

P10. Bernhardsson B. and M. Sternad (1993)
Feedforward control is dual to deconvolution. *Int. J. Control*, vol 57, pp 393–405.

P11. Sternad M. and A. Ahlén (1993)
Robust Wiener filtering based on probabilistic descriptions of model errors. Invited paper, to appear in *Kybernetica*, vol 29.

P12. Ahlén A. and M. Sternad (1994)
Filter design via inner–outer factorization: Comments on "Optimal deconvolution filter design based on orthogonal principle". To appear in *Signal Processing*, vol 35 no 1.

P13. Öhrn K., A. Ahlén and M. Sternad (1993)
A probabilistic approach to multivariable robust filtering and open–loop control. Submitted. Also available as Report UPTEC 93008R, Systems and Control Group, Uppsala University.

P14. Lindbom L. and K. Jamal (ERA) (1993)
An improved low–complexity model channel estimation algorithm for fading channels. Patent application, USA.

Conference papers:

C1. Ahlén A. and M. Sternad (1989)
Adaptive input estimation. *ACASP 89, IFAC Symposium on Adaptive Systems in Control and Signal Processing*, Glasgow, UK, April 1989, vol 2, pp 631–636.

C2. Sternad M. (1989)
The use of disturbance measurement feedforward in LQG self–tuners. ACASP'89, pp 353-358.

C3. Sternad M. and A. Ahlén and (1991)
Filter design using polynomial equations. Invited paper, *IEE Colloquium on Polynomial Methods in Optimal Control and Filtering*, London, UK, May 1991.

C4. Ahlén A. and M. Sternad (1991)
Adaptive deconvolution based on spectral decomposition. Invited paper, *SPIE Annual Symposium on Adaptive Signal Processing*, San Diego, USA, July 1991, vol 1565, pp 130–142.

C5. Sternad M. and A. Ahlén (1992)
Robust filtering based on probabilistic descriptions of model errors. *IFAC Workshop on System Structure and Control*, Prague, September 3–5, 1992, pp 156–159.

C6. Sternad M. and A. Ahlén (1992)
Robust feedforward control based on probabilistic descriptions of model errors. *Swedish control meeting "Reglermöte"*, Chalmers university, Gothenburg, November 4–5, 1992.

C7. Sternad M. and A. Ahlén and E. Lindskog (1993)
Robust decision feedback equalization.
ICASSP'93, Minneapolis, April 27-30 1993, vol III, pp 555-558.

C8. Lindbom L. (1993)
Simplified Kalman estimation of fading mobile radio channels: high performance at LMS computational load. (Poster) ICASSP'93, Minneapolis, April 27-30 1993, vol III, pp 352-355.

C9. Graebe S. and A. Ahlén (1993) Robust transfer among alternative controllers. *12th IFAC World Congress*, Sydney, Australia, July 1993.

NUTEK Conference contributions.

N1. Ahlén A. and M. Sternad (1988)
Adaptive Wiener filters in control and signal processing: recent results. Lund, May 1988.

N2. Ahlén A. and M. Sternad (1989)
Orthogonality evaluated in the frequency domain: a new and simple tool for deriving optimal IIR–filters. Stockholm, May 1989.

N3. Sternad M., A. Ahlén and L. Lindbom (1989)
Cancelling of acoustic motor noise in mobile radio systems. Stockholm, May 1989.

N4. Lindbom L., M. Sternad and A. Ahlén (1991)
A Viterbi detector based on sinusoid modelling of fading mobile radio channels: An illustration of the utility of deterministic models of time variations in adaptive systems. (Poster) Gothenburg, May 1991.

N5. Ahlén A. and M. Sternad (1992)
Adaptive Wiener filters in control and signal processing. Uppsala, May 1992.

N6. Sternad M. and A. Ahlén (1992)
Robust decision feedback equalizers. (Poster) Uppsala, May 1992.

N7. Lindbom L. (1992)
Simplified Kalman estimation of fading mobile radio channels: high performance at LMS computational load. Uppsala, May 1992.