CENIIT FINAL PROJECT REPORT

– Flexible Frequency-Band Reallocation

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A. Major Technical Results in Brief

A new technique for flexible frequency-band reallocation has been developed that can substantially outperform the existing ones when all desired aspects such as *flexibility*, *low complexity and inherent parallelism*, *perfect frequency-band reallocation (PFR)*, *spectral efficiency*, and *simplicity* are *simultaneously* considered. In particular, compared with previous techniques that can approximate PFR as close as desired, the new technique may have one or two orders of magnitude lower complexity. The core of the proposed technique is a novel on-line variable oversampled complex-modulated filter bank.

New principles for single- and multi-parameter estimation in relation to time-interleaved A/D-converters have been developed. These estimation techniques have excellent convergence and accuracy properties and have been important milestones in the development of advanced A/D-converter principles. Further, low-complexity reconstruction principles for A/D-converter interleaving mismatch have been developed which support 16-bit resolution reconstruction.

Novel, very promising principles for transmultiplexing (the process of transmitting multiple data streams on a single channel with little or no interference between the transmitted signals) have been developed. These all fit well with and can be used together with the developed flexible frequency-band reallocation networks.

The above mentioned project contributions have been published in international scientific journals.

B. Short Project Description

The future society foresees globally interconnected digital communication systems offering multimedia services, information on demand, and delivery of information (data) at high data rates and low cost and with high performance. Terrestrial networks can in principle meet the requirements on communication capacity due to the practically unlimited bandwidth provided by fibre optic cables. However, very large investments are required to bridge the distance between the local exchange and the customer. Using satellites to provide network access has a number of advantages compared with terrestrial wideband access methods. However, in order to meet the requirements of the communication systems of tomorrow, it is imperative to develop a new generation of satellite systems, payload architecture, ground technologies, and techniques combining flexibility with cost efficiency. Further, in order to use the limited available frequency spectrum efficiently, the satellite on-board signal processing must support frequency-band reuse among the beams and also flexibility in bandwidth and transmitted power allocated to each user; and, dynamic frequency allocation is desired for covering different service types requiring different data rates and bandwidths. One major issue in this next-generation satellite-based communication system is therefore the *on-board reallocation of information*. In technical terms, this calls for digital *flexible frequency-band reallocation networks*[1] which thus are critical components.

Terrestial communication networks today are supplemented with so called repeaters in order to support long-range coverage and full network functionality in the absence of line of sight radio links. These radio transceivers receive and re-transmit signals with the purpose of increasing signal power or extending the coverage to for example tunnels and indoor areas. Traditionally, these repeaters are realized using analog circuits but there is an

1. Frequency-band reallocation is also referred to as frequency multiplexing and demultiplexing.

increasing interest in digital realizations. The digital frequency-band reallocation networks developed in this project are eminently suitable for this purpose.

The principle architecture of a digital transparent communication node is shown in Fig. 1.

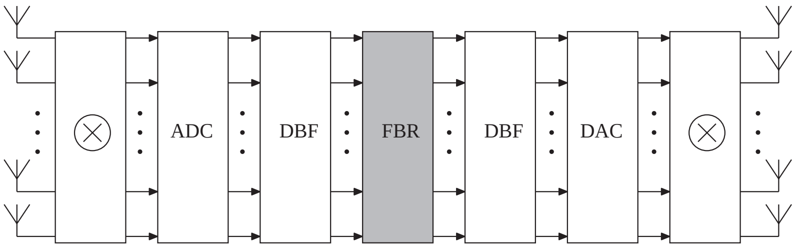

Figure 1. Principle architecture, describing the signal processing of a transparent communication node.

An antenna matrix receives a combination of signals from multiple sources. These are then frequency demodulated, converted into a digital representation (ADC) and beamformed digitally (DBF). The signals are further switched (FBR) before being transmitted through multi-spot beams. The number of input signals can in general differ from the number of output signals, and the input and output signals can generally use different bandwidths and data rates.

Today, the interface circuits, A/D-converters, are not experiencing as high development pace as digital circuit technology and these have become bottle-neck components in many applications. In order to realize the architecture illustrated above and substantially increase the performance of these components, new principles for A/D conversion have to be developed. One can foresee that one way to alleviate the bandwidth/resolution limitation of A/D-converters is to make use of parallelism and to exploit the very rapid development and extreme capacity of digital circuit technology. Such a principle is interleaving of A/D-converters together with digital signal processing to remove the errors induced by circuit mismatch.

C. Use of Funding

The CENIIT funding has mainly supported the salary of the project leader and two Ph. D. students at the division of Electronics Systems, Erik Säll and Amir Eghbali. The project leader has acted co-supervisor of the two, having the supervisors Prof. Mark Vesterbacka and Prof. Håkan Johansson, respectively. Erik's involvement in the project work was on analog-to-digital converters while Amir is working on the flexible frequency-band reallocation and transmultiplexers.

D. Promotions and Theses Outcome

At current date, the project leader's application for the degree Docent in Electronics Systems is being processed. During the project work, the project leader has co-supervised four Ph. D. students with thesis topics related to this project:

- Erik Säll - Ph. D. May 2007, "Implementation of flash analog-to-digital converters in silicon-on-insulator CMOS technology", with main supervisor being Prof. Mark Vesterbacka.
- Linnéa Rosenbaum - Ph. D. June 2007, "On low-complexity frequency selective digital filters and filter banks", with main supervisor being Prof. Håkan Johansson.
- Mattias Olsson - Ph. D. June 2008, "Contributions to delay, gain, and offset estimation", with main supervisor Prof. Håkan Johansson.
- Amir Eghbali - Lic. thesis to be presented in March 2009, with main supervisor being Prof. Håkan Johansson.

The project leader has supervised and examined a number of Master Thesis projects during the course of the projects. Two very successful projects which are relevant to the scope of this project are:

- Krister Berglund, Oskar Matteusson, "On the realization of switched-capacitor integrators for sigma-delta modulators", 2007.

- Hanna Svensson, “Study on a second-order bandpass SD-modulator for flexible AD-conversion“, 2008.

E. Publication Outcome

During the course of this project, scientific results have been published as 9 journal publications and 17 peer-reviewed conference publications. These are listed below.

Journal publications

[1] H. Johansson and P. Löwenborg, "Reconstruction of nonuniformly sampled bandlimited signals by means of time-varying discrete-time FIR filters," *J. Applied Signal Processing - Special Issue on Frames and Overcomplete Representation in Signal Processing, Communications, and Information Theory,* vol. 2006, Article ID 64185, 18 pages, 2006.

[2] P. Löwenborg and H. Johansson, "Minimax design of adjustable-bandwidth linear-phase FIR filters," *IEEE Trans. Circuits Syst. I*, vol. 53, no. 2, pp. 431-439, Feb. 2006.

[3] H. Johansson and P. Löwenborg, "Flexible frequency-band reallocation network using variable oversampled complex-modulated filter banks," EURASIP Journal on Advances in Signal Procesing, vol. 2007, Article ID 63714, 15 pages, 2007. doi: 10.1155/2007/63714.

[4] L. Rosenbaum, P. Löwenborg, and H. Johansson, "An approach for synthesis of modulated M-channel FIR filterbanks utilizing the frequency-response masking technique," *EURASIP Journal on Advances in Signal Processing*, vol. 2007, Article ID 68285, 13 pages, 2007. doi: 10.1155/2007/68285.

[5] H. Johansson, P. Löwenborg, and K. Vengattaramane, "Least-squares and minimax design of polynomial impulse response FIR filters for reconstruction of two-periodic nonuniformly sampled signals," *IEEE Trans. Circuits Syst. I* , vol. 54, no. 4, pp. 877-888, April 2007.

[6] A. Blad, H. Johansson, P. Löwenborg, "Multirate formulation for mismatch sesitivity analysis of analog-to-digital converters that utilize parallel sigma-delta-modulators," *EURASIP Journal on Advances in Signal Processing,* vol. 2008, Article ID 289184, 11 pages, 2008, doi:10.1155/2008/289184.

[7] A. Eghbali, H. Johansson, and P. Löwenborg, "A multimode transmultiplexer structure," *IEEE Trans. Circuits Syst. II - Special Issue on Multifunctional Circuits and Systems for Future Generations of Wireless Communications*, vol. 55, no. 3, pp. 279-283, Mar. 2008.

[8] H. Johansson and P. Löwenborg, "A least-squares filter design technique for the compensation of frequency-response mismatch errors in time-interleaved A/D converters," provisionally accepted for *IEEE Trans. Circuits Syst. II.*

[9] A. Eghbali, H. Johansson, and P. Löwenborg, "Flexible frequency-band reallocation: complex versus real," *Circuits, Systems and Signal Processing.* (Accepted).

Peer-reviewed conference publications

[10] H. Johansson and P. Löwenborg, "*Reconstruction of nonuniformly sampled bandlimited signals using time-varying discrete-time FIR filters,* "XII European Signal Processing Conf., Vienna, Austria, Sept. 6-10, 2004.

[11] M. Olsson, P. Löwenborg, and H. Johansson, "*Scaling of multistage interpolators,* "XII European Signal Processing Conf., Vienna, Austria, Sept. 6-10, 2004.

[12] M. Olsson, P. Löwenborg, and H. Johansson, "Scaling and round-off noise in multistage interpolators and decimators," in Proc. Fourth Int. Workshop Spectral Methods Multirate Signal Processing, Vienna, Austria, Sept. 11-12, 2004.

[13] H. Johansson and Per Löwenborg, "*Reconstruction of periodically nonuniformly sampled bandlimited signals using time-varying FIR filters,*" in Proc. Fourth Int. Workshop Spectral Methods Multirate Signal Processing, Vienna, Austria, Sept. 11-12, 2004.

[14] H. Johanson and P. Löwenborg, "*Flexible frequency-band reallocation networks based on variable oversampled complex-modulated filter banks,*" in Proc. IEEE Int. Conf. Acoust. Speech Signal Proc., Philadelphia, Mar. 2005.

[15] H. Johansson, P. Löwenborg, and K. Vengattaramane, "*Reconstruction of two-periodic nonuniformly sampled signals using polynomial impulse response time-varying FIR filters*," IEEE Int. Symp. Circuits Syst., Kos Island, Greece, May 21-24, 2006.

[16] M. Olsson, H. Johansson, and P. Löwenborg, "*Delay estimation using adjustable fractional delay all-pass filters*," in Proc. IEEE Nordic Signal Processing Symp., Reykjavik, Iceland, June 7-9, 2006.

[17] H. Johansson, P. Löwenborg, and Kameswaran Vengattaramane, "*Reconstruction of M-periodic nonuniformly sampled signals using multivariate polynomial impulse response time-varying FIR filters,*" in Proc. XIV European Signal Processing Conf., Florence, Italy, Sept. 4-8, 2006.

[18] L. Rosenbaum, H. Johansson, and P. Löwenborg, "*Oversampled complex-modulated causal IIR filter banks for flexible frequency-band reallocation networks*," in Proc. XIV European Signal Processing Conf., Florence, Italy, Sept. 4-8, 2006.

[19] M. Olsson, H. Johansson, and P. Löwenborg, "*Time-delay estimation using Farrow-based fractional-delay FIR filters: Filter approximation vs. estimation errors,*" in Proc. XIV European Signal Processing Conf., Florence, Italy, Sept. 4-8, 2006.

[20] A. Blad, P. Löwenborg, and H. Johansson, "*Design trade-offs for linear-phase FIR decimation filters and SD-modulators*," in Proc. XIV European Signal Processing Conf., Florence, Italy, Sept. 4-8, 2006.

[21] A. Blad, H. Johansson, and P. Löwenborg, "*A general formulation of analog-to-digital converters using parallel sigma-delta modulators and modulation sequences*," in Proc. Asia-Pacific Conference on Circuits and Systems, Singapore, Dec. 4-7, 2006.

[22] A. Eghbali, H. Johansson, and P. Löwenborg, "*An arbitrary bandwidth transmultiplexer and its application to flexible fre-*

quency-band reallocation networks," in Proc. European Conf. Circuit Theory Design, Seville, Spain, Aug. 26-30, 2007.

[23] A. Eghbali, H. Johansson, and P. Löwenborg, "*Flexible frequency-band reallocation MIMO networks for real signals*," in Proc. Int. Symp. Image, Signal Processing, Analysis, Istanbul, Turkey, Sept. 27-29, 2007.

[24] A. Eghbali, O. Gustafsson, H. Johansson, and P. Löwenborg, "*On the complexity of multiplierless direct and polyphase FIR filter structures*," in Proc. Int. Symp. Image, Signal Processing, Analysis, Istanbul, Turkey, Sept. 27-29, 2007.

[25] M. Olsson, H. Johansson, and P. Löwenborg, "*Simultaneous estimation of gain, delay, and offset utilizing the Farrow structure,*" in Proc. European Conf. Circuit Theory Design, Seville, Spain, Aug. 26-30, 2007.

[26] A. Eghbali, H. Johansson, and P. Löwenborg, "*A Farrow-structure-based multi-mode transmultiplexer,*" in Proc. IEEE Int. Symp. Circuits Syst., Seattle, Washington, USA, May. 18-21, 2008.

F. Industrial Cooperation

The project leader and Prof. Håkan Johansson are two of the co-founders of Signal Processing Devices Sweden AB (SP Devices), located in Mjärdevi, Linköping. The company has at present about 20 employees and offers licensing of signal processing IP blocks for instrumentation, radar, communications, and signals intelligence equipment.

The industrial co-operation of this project has mainly been done through this LiTH spin-off company. During this project, principles and algorithms for mismatch parameter estimation in time-interleaved A/D-converters have been developed as well as reconstruction principles for mismatch error compensation. These research results are today realized in SP Devices products. An example of this is shown in Figure 2.

Figure 2. A data acquisition board utilizing principles for error correction developed during the CENIIT project. The board is the state-of-the-art for 14-bit resolution A/D-conversion supporting a sampling frequency of 840 MSps.

Further, the principles for flexible frequency-band reallocation developed during the project has also been transferred to SP Devices and is today the back-bone of in one of the company's digital signal processing IP for circuit switching which finds applications in communication equipment.

G. Cooperation with Other CENIIT Projects

This project has been performed in close cooperation with the Prof. Håkan Johansson who has been funded by CENIIT during the period 2001 - 2007 (Proj.: Konstruktion och implementering av signalbehandlande system).

Finally, the project leader would like to take the opportunity to thank the CENIIT counsel for the valuable financial support.