Application

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Information about application

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Descriptive data

Project info

Project title (Swedish)*

Massivt Parallell Digital Signalbehandling för Multi-Tb/s Optisk Kommunikation

Project title (English)*

Massively Parallel Digital Signal Processing for Multi-Tb/s Optical Communication

Abstract (English)*

Optical communication together with advanced digital signal processing (DSP) constitute enablers for the current and future Internet traffic. However, the exponential growth of traffic capacity demands imposes extreme requirements on the underlying optical and electrical infrastructure, not only in terms of data rates and bandwidths, but also in terms of energy consumption. It has recently been reported that the energy consumed by the information and communication technology is foreseen to be doubled from 2-4% to 4-8% of the total carbon emissions by the end of this decade. Hence, it is imperative to address not only bandwidth constraints but also energy efficiency to enable future multi-terabits per second (multi-Tb/s) optical-channel communication. In addition, there is a need to support varying bandwidth and transmission capacity to meet the increasing demands for elastic heterogeneous networks. This project aims at increasing the energy efficiency of the electrical infrastructures by developing and designing efficient massively parallel DSP algorithms and architectures for vital functions. The focus is on algorithms that are always needed to mitigate errors that inevitably arise in optical channels, like chromatic dispersion. The objective is to achieve orders-of-magnitude-reduced implementation complexities with maintained transmission capacity.

Popular scientific description (Swedish)*

Optisk kommunikation tillsammans med avancerad digital signalbehandling är grunden för nuvarande och framtida Internet-trafik. Emellertid ökar kapacitetsbehovet hos datatrafiken exponentiellt vilket leder till extrema krav på den optiska och elektriska infrastrukturen. Kraven ökar inte enbart vad gäller högre datahastigheter och mer bandbredd, utan även energieffektiviteten behöver förbättras. Det har nyligen rapporterats att energin som konsumeras av informations- och kommunikationsteknologier förväntas fördubblas från 2-4% till 4-8% av de totala koldioxidutsläppen vid slutet av detta decennium. Det är således viktigt att adressera inte bara bandbreddsbegränsningar utan också energieffektivitet för att möjliggöra framtida kommunikationskanaler med datakapaciteter av flera tera-bitar per sekund (multi-Tb/s). Dessutom finns ett ökat behov av att stödja varierande bandbredder och kapacitetskrav för att möta de ökande kraven på elastiska (avstämbara) heterogena nätverk.

Trenden för att skapa energieffektiva kommunikationskanaler med datakapaciteter av multi-Tb/s går mot så kallade heloptiska nätverk. Informationsgenereringen och signalbehandlingen som krävs för att pålitligt överföra informationen sker dock fortfarande i den elektriska domänen. Hela nätverket består med andra ord av både optiska och elektriska delar samt gränssnitt mellan dem. För att erhålla ett energieffektivt nätverk är det därför inte tillräckligt att reducera kostnaden enbart i den optiska delen utan även i den elektriska delen. Kostnaden i den senare beror i hög grad på effektiviteten hos den digitala signabehandlingen och algoritmerna som används. Vid till exempel en datahastighet av 1Tb/s förbrukar en vanlig multiplikation i storleksordningen 1 watt i moderna teknologier. Enklare algoritmer kan kräva många tusen aritmetiska operationer vid den hastigheten vilket skulle leda till en effektförbrukning på flera kilowatt. Det är således viktigt att radikalt öka effektiviteten.

Syftet med detta projekt är att mångfalt öka effektiviteten i den elektriska infrastrukturen genom utveckling och design av effektiva digital algoritmer för centrala funktioner. Speciellt fokuserar vi på funktioner som är väldigt beräkningsintensiva och ineffektiva då enklare algoritmer används. Särskild vikt läggs på algoritmer som alltid behövs för att korrigera för fel som oundvikligen sker i optiska kanaler. Ett exempel är algoritmer för korrigering av så kallad kromatisk dispersion som ger upphov till frekvensberoende fördröjning, vilket medför kraftig distorsion. En nyckel här är användandet av massivt parallella algoritmer. Sådana algoritmer behövs för att hantera väldigt höga datahastigheter, men de kan också utnyttjas för att radikalt sänka beräkningskomplexiteten.

Kunskapen som genereras i projektet kan användas för att konstruera mer energieffektiva elektriska infrastrukturer för optisk kommunikation. Den har även ett bredare användningsområde då kraven ständig ökar på mer energieffektiv signalbehandling. Resultaten i projektet är således användbara generellt för konstruktion av energieffektiv och högpresterande signalbehandling och kommunikation.

Project period

Number of project years*

4

Calculated project time*

2016-01-01 - 2019-12-31

Classifications

Select a minimum of one and a maximum of three SCB-codes in order of priority.

Select the SCB-code in three levels and then click the lower plus-button to save your selection.

SCB-codes*	2. Teknik > 202. Elektroteknik och elektronik > 20205. Signalbehandling

Enter a minimum of three, and up to five, short keywords that describe your project.

Keyword 1*

DSP-Algorithms

Keyword 2*

Energy-Efficiency

Keyword 3*

Massive Parallelism

Keyword 4

Optical Communication

Keyword 5

Error Correction

Ethical considerations

Specify any ethical issues that the project (or equivalent) raises, and describe how they will be addressed in your research. Also indicate the specific considerations that might be relevant to your application.

Reporting of ethical considerations*

Etiska frågor ej aktuella.

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

Massively Parallel Digital Signal Processing for Multi-Tb/s Optical Communication

Håkan Johansson and Oscar Gustafsson

March 30, 2015

1 Purpose and Aims

Optical communication together with advanced digital signal processing (DSP) constitute enablers for the current and future Internet traffic [1]. However, the exponential growth of traffic capacity demands imposes extreme requirements on the underlying optical and electrical infrastructure, not only in terms of data rates and bandwidths, but also in terms of energy consumption. It has recently been reported that the energy consumed by the information and communication technology is foreseen to be doubled from 2-4% to 4-8% of the total carbon emissions by the end of this decade [2]. Hence, it is imperative to address not only bandwidth constraints but also energy efficiency to enable future multi-terabits per second (multi-Tb/s) optical-channel communication. In addition, there is a need to support varying bandwidth and transmission capacity to meet the increasing demands for elastic heterogeneous networks. This project aims at increasing the energy efficiency of the electrical infrastructures by developing and designing efficient massively parallel DSP algorithms for vital functions. The focus is on algorithms that are always needed to mitigate errors that inevitably arise in optical channels, like chromatic dispersion. As the architecture will have an impact on the operation cost, this is also considered in the project. The objective is to achieve orders-of-magnitude-reduced implementation complexities with maintained transmission capacity.

2 Survey of the Field

To create energy-efficient communication-channel capacity of multi-terabits per second (multi-Tb/s) and beyond, the trend is to make use of so called all-optical networks. However, the generation of information and signal processing required for reliable transmission take place in the electrical domain. The overall network thus consists of optical channels, information generation and signal processing in the electrical domain, and optical/electrical interfaces. This is exemplified in Fig. 1. To obtain an overall energy-efficient network, it is not sufficient to reduce the cost of the optical infrastructure alone, but also of the electrical infrastructure which in turn depends on the efficiency of the DSP algorithms that are used. To exemplify, based on the results in [3], one can estimate that performing one 16x16-bit multiplication per sample at a data rate of one tera sample per second (TS/s) will require a power consumption in the order of 1 watt (W) in modern deep submicron technologies. Straightforward algorithms may require several hundreds or thousands of arithmetic operations per sample [4–6], which would imply a power consumption in the order of kilowatts (kW). It is therefore necessary to substantially increase the efficiency of the electrical infrastructure which is the aim of this project. The focus is on the development and design of new efficient DSP algorithms and architectures for the mitigation of errors that inevitably arise in the optical channels. The objective is to achieve orders-of-magnitude-reduced implementation complexities with maintained transmission capacity. A key

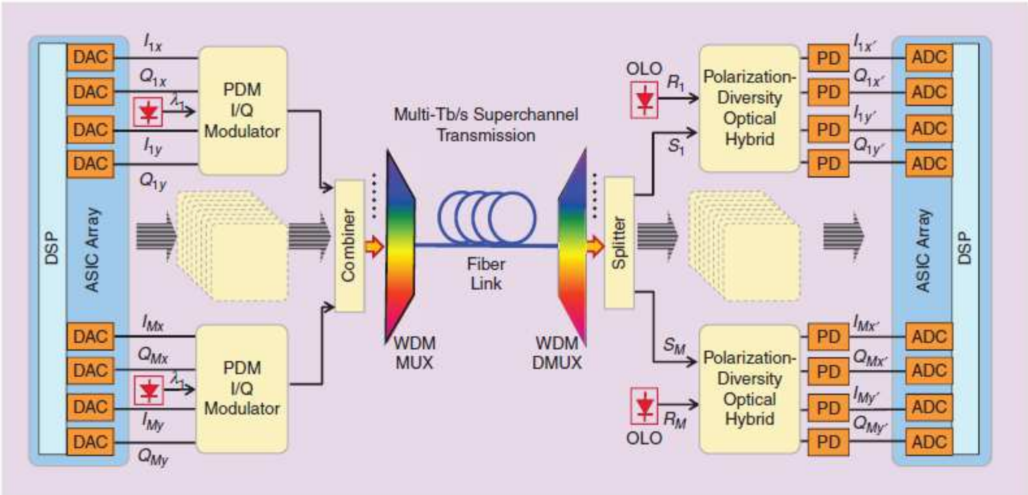

Figure 1: Illustration of electrical-optical-electrical multi-Tb/s transmission (Figure taken from [1]).

here is the use of massive parallel processing, enabled through subband processing. This is required to enable very high data rates, but can also be utilized to reduce the computational complexity of the DSP and thus increase the energy efficiency [7].

2.1 DSP Techniques for Mitigation of Errors in Optical Channels

There are several features that distinguish optical and electrical media, which calls for new advanced DSP algorithms and implementation techniques [8, 9]. In this project, we address the mitigation of errors that inevitably occur in the optical channels. The focus is on computationally challenging tasks, like chromatic dispersion, polarization mode dispersion, I/Q channel mismatches, and fiber nonlinearities. There are also other types of problems that are important to address, like phase noise mitigation, but they are not primarily in focus in this project.

Especially the chromatic-dispersion mitigation becomes a major part of the receiver (Rx) DSP computational complexity when the data rates increase [8]. This is because the chromatic dispersion then causes very long delay spread of hundreds or even thousands of symbols (samples). This calls for a very long equalization filter [6], whose straightforward implementation in the time domain (linear convolution) requires several hundreds or thousands of multiplications per sample. At a TS/s data rate, this implies an enormous amount of computations per second which leads to a very high power consumption in the kW region. The complexity of the convolution can be reduced substantially by implementing the filter in the frequency domain via efficient FFTs and overlap-save or overlap-add methods [10]. These methods can be viewed as special cases of a general subband-based scheme [11, 12]. The generalization offers more freedom in the design and implementation which enables further complexity reductions compared to the solution where a single regular equalizer is first optimized (as in [6]) and subsequently implemented in the frequency domain. The general subband-based scheme is particularly attractive for the efficient implementation of elastic mitigation algorithms because it enables simplified online adaptation.

Subband-based processing has the potential to reduce the computational complexity by orders of magnitude, as compared to straightforward solutions [7]. In the subband-based approach, a wide-band digital signal (e.g. one of the optical Gb/s subchannels in an optical multi-Tb superchannel) is then parallelized into a number of narrow-band channels via an analysis filter bank whose channel outputs are subsequently downsampled. Then, in the present context, low-order subband mitigation takes place in each channel, after which the composite wide-band

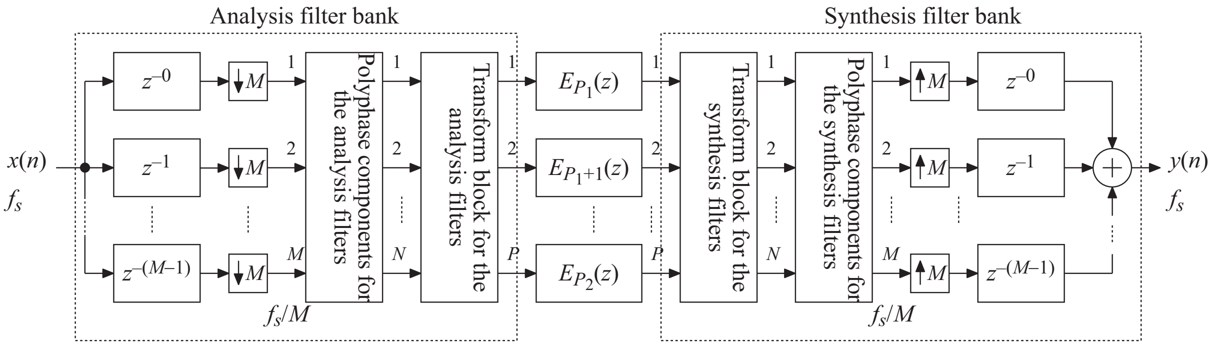

Figure 2: Efficient low-rate implementation of subband-based equalization.

signal can be obtained through a synthesis filter bank. Using efficient modulated filter banks and polyphase decomposition [13], which allows the filtering operations to take place at a lower sampling rate (depicted in Fig. 2), orders-of-magnitude complexity savings may be achieved. However, up till now (e.g., [8, 11]), the focus has mainly been on the basic principles and examples with sparse constellation diagrams (like 4-QAM) and relatively large bit error rates (like 0.001). In such cases, the approximation errors that are inevitably introduced in the filter banks and subband processing can be relatively large without affecting the quality of the transmission. On the other hand, with more dense constellation diagrams and smaller bit error rates, which are required to support elastic high-capacity systems, it becomes more challenging to design the overall subband-based mitigation algorithms. This is the focus of this project (see Section 3.1).

3 Project Description

3.1 Theory and Method

In this project, we will address the design of massively parallel subband-based mitigation algorithms and architectures and explore the huge design space. As mentioned above, the focus has up till now mainly been on the basic principles and examples with sparse constellation diagrams and relatively large bit error rates, in which cases the overall design can be carried out quite comfortably. Here, we will address the more challenging task of designing the overall subband-based mitigation algorithms for more stringent requirements which are required for denser constellation diagrams and smaller bit error rates. It is desired to use denser constellation diagrams in order to transmit more bits per time unit [9]. Furthermore, to cope with very high data rates, it is necessary to increase the degree of parallelism when designing the algorithms. This means that filter banks with thousands of channels need to be employed. The design of high-capacity algorithms based on such massive parallelism goes well beyond what has been reported in the literature so far. Taking also into account that there is an additional desire to have elastic algorithms, the design becomes very challenging.

We will adopt an optimization-based design approach in the project, and the research will be carried out through the four interactive subtopics as detailed in the subsections below. Initially, we will focus on chromatic-dispersion mitigation, as reflected in the subsequent discussions. Later on in the project, the results will be extended to the other types of errors mentioned earlier and their interaction. The main difference lies in the behavior of the submitigators, whereas the filter banks have essentially the same function in all cases but may differ when it comes to the design. For linear errors in the optical channel (like chromatic dispersion), as well as polarization mode dispersion [1, 14] and I/Q mismatches [15–17], the submitigators are linear inverse/correction systems. For nonlinearity mitigation, one may generally use Volterra series inverses, but such inverses tend to be computationally intensive [18]. Therefore, we aim to use simplified schemes based on parallel linear-nonlinear-linear (LNL) systems which have been adopted in other contexts, like linearization of analog-to-digital converters [19, 20] (also see Section 3.1.4 below).

3.1.1 Optimization of Massively Parallel Subband-Based Mitigation Algorithms

Here, we address the optimization of massively parallel mitigation algorithms. This corresponds to the optimization of massively parallel multirate filter banks but with additional subband mitigators (E_k). Here, optimization means to optimize all subfilters simultaneously in order to achieve the lowest possible overall complexity for a given mitigation problem and acceptable approximation error. However, a straightforward optimization of these schemes, with independent filter parameters, is difficult and time consuming (several hours or even days). This is because: a) many channels correspond to a large number of filter parameters (coefficients), in the order of tenths or hundreds of thousands [21], as well as many constraints; b) the optimization problem is nonconvex due to the cascaded subfilters (which requires carefully selected initial solutions [21]). Furthermore, due to the additional subband equalizers (E_k), the problem becomes even more challenging than that of massively parallel regular filter banks, which is challenging on its own. In regular filter banks, it suffices to design the frequency selective channel filters (typically carried out via one prototype filter design when using modulated filter banks) and the overall filter bank to suppress aliasing and approximate a pure delay. Here, on the other hand, one has to incorporate the subband blocks and the overall scheme is to approximate the desired function for the problem at hand. For chromatic-dispersion mitigation, the desired equalizing function is $\exp(jK(\omega T)^2)$ in the frequency domain, where $K = \frac{P\lambda^2 d}{4\pi c T^2}$ with P, λ, d, c, denoting the fiber dispersion parameter, wavelength, fiber length, and speed of light, respectively [4, 5]. Further, $\omega T = 2\pi f T$ denotes the digital angular frequency, with T being the sampling period used when acquiring the digital signal on the receiver side.

Our work here is inspired by our recent results in [21, 22], where polynomial impulse responses are utilized for the design of many-channel regular filter banks and transmultiplexers (TMUXs) with arbitrarily small approximation errors. A key is to parameterize the overall very long impulse response in such a way that it is expressible in terms of many a priori fixed coefficients and fewer unknown (free) parameters to be determined in the optimization. For frequency selective (typically lowpass prototype) filters, an appropriate way is to represent each impulse response value as a polynomial of a certain degree. Our observation in [22] is that the number of free parameters can be further reduced, as compared with the method in [21], by polyphase decomposing the polyphase components (fractional-delay subfilters) of frequency selective filter transfer functions. To exemplify, the R polyphase components of a lowpass filter, with a digital bandwidth of π/R, correspond to R distinct fractional-delay filters with delay values of $d_r = r/R$, $r = 0, 1, \ldots R-1$. Then, by further polyphase decomposing these fractional-delay filters, we showed in [22] that they can be represented as follows by their transfer functions in the z-domain:

$$H_r(z) = \sum_{m=0}^{M-1} z^{-m} \alpha_m \sum_{p=0}^{L} d_m^p G_p(z^M) \tag{1}$$

where

$$d_m = \frac{d_r - m}{M}, \quad \alpha_m = \frac{1}{M} \frac{\sin\left(\pi(d_r - m)\right)}{\sin\left(\frac{\pi(d_r - m)}{M}\right)} \tag{2}$$

and

$$G_p(z) = \sum_{n=0}^{N_G} g_p(n) z^{-n} \tag{3}$$

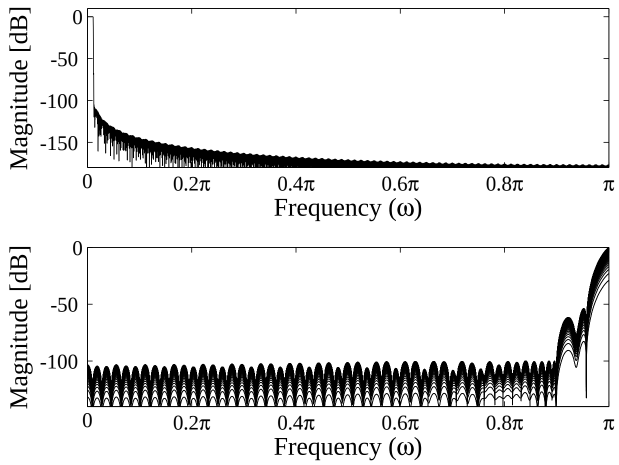

Figure 3: Example of few-parameter optimization of high-order filters. Upper plot: Magnitude response of a 88th-band lowpass filter of order 9504, designed through the optimization of only 10 parameters. Lower plot: Approximation error modulus of the corresponding polyphase components (fractional-delay filters).

with N_G denoting the order of $G_p(z)$. The overall lowpass filter transfer function can then be expressed in the form of

$$H(z) = \sum_{r=0}^{R-1} z^{-r} H_r(z^R) = \sum_{r=0}^{R-1} z^{-r} \sum_{m=0}^{M-1} z^{-mR} \alpha_m \sum_{p=0}^{L} d_m^p G_p(z^{MR}). \tag{4}$$

In the filter design, the only parameters to be determined are the subfilter impulse responses $g_p(n)$, since d_m and α_m are determined a priori by (2)–(3). Further, low-order subfilters $G_p(z)$ can be used, meaning that only a few free parameters need to be determined, because a high-order overall filter $H(z)$ is obtained through the transformation $z \to z^{RM}$. An example is seen in Fig. 3 which plots the magnitude response of a 88th-band lowpass filter with a transfer function in the form of (4) with $R = 88$. Here, we have used $M = 36$, $L = 7$, and second-order ($N_G = 2$) FIR subfilters $G_p(z)$ with symmetric (anti-symmetric) impulse responses for even (odd) values of p. This means that only 10 free impulse response values (parameters) were determined in the optimization of the overall filter of the high order 9504. This shows that we can design high-capacity and high-order filters through very few-parameter optimization.

A way to further simplify the design is to overdesign the filter-bank channel filters (prototype filter in modulated filter banks) which enables a relaxation of the number of constraints. In particular, it is possible to exclude all aliasing-terms constraints in the optimization, as they via the overdesign are ensured to be suppressed to the level of the filters' stopband attenuation. However the overdesign will also lead to a higher filter order and complexity than necessary. In the project, we will also consider this option and use it as a benchmark, against which we will compare the more efficient non-relaxed optimized solutions.

Based on the principles explained above, we aim at developing systematic design techniques for massively parallel subband-based mitigation. As mentioned earlier, the additional subband mitigators add a further challenge to the problem. Based on these systematic design techniques, we aim to explore the design space and derive formulas that give the optimal values of the number of channels and subfilter orders as functions of the error function parameter (K for chromatic dispersion), bandwidth, and transmission quality (bit error rate). In this study, both finite-length and infinite-length impulse response (FIR and IIR) filters will be studied. Whereas regular IIR filtering cannot be used at very high sampling rates (due to their recursive nature which bounds the sampling rate), the subband-based approach opens up for the use of them since all filtering then takes place at a reduced data rate. Depending on the specification and approximation problem, IIR filters may have a lower complexity than the FIR counterparts and may thus increase the energy efficiency. A goal here is also to derive fundamental bounds on the computational complexity required for subband-based mitigation.

3.1.2 Elastic Schemes

There is an increasing demand for elastic DSP which can efficiently adapt to varying conditions (e.g., different fiber lengths) and requirements in order to avoid wasting energy. In principle, we can use the scheme above, but this would require online redesign for each mode which is expensive and time consuming. Instead, we will here extend the basic subband-based schemes to elastic schemes that can be easily adapted without redesign and that are elastic both in terms of functionality and in terms of transmission quality. The latter translates to subfilters (subblocks) with adaptable approximation errors and wordlengths.

The inspiration for this part of the project is our recent result and observation as noted above, and our work on online adaptable DSP algorithms based on polynomial impulse responses [23]. With this as a starting point, the overall subband-based scheme will be divided into fixed analysis and synthesis filter banks and online variable subband mitigators. A major challenge here is to, offline, design the fixed parts of the overall scheme in such a way that a given transmission quality is ensured for all possible modes within a certain subband mitigator parameter space. Once the fixed parts have been determined offline, the variable parts are updated online by changing a few parameters through appropriate adaptive algorithms.

3.1.3 Architecture Impact

The computational complexity is often a good first-order approximation of the related computational energy. However, in some cases, such as the highly parallel architectures needed here, it is likely that the operator cost may differ significantly between different architectures. First, it can be noted that although the number of operations per sample is drastically reduced by the proposed schemes, the sample rate it so high that existing processor architectures will not be efficient, even high-end massively parallel graphics processor units (GPUs) will have problems coping with the computational load and throughput requirements. In addition, since the computations are well known in advance, the flexibility of a general-purpose processor will become a significant energy overhead [24].

Instead, the proposed algorithms will have to be implemented as (parts of) dedicated integrated circuits to reach the full potential of energy efficiency. Considering existing and forthcoming implementation technologies for integrated circuits they all have a maximum clock frequency that the circuit can be operated with. While some digital circuits have been reported that are clocked at about 10 GHz, it is often more reasonable to aim at a clock frequency in the GHz range, especially for the relatively large circuits that are considered here. In any case, these numbers are significantly lower than the data rates foreseen for the applications. Hence, the architecture will process several data streams in parallel. From an implementation perspective we are facing a trade-off depending on the ratio between the sample (data) rate and the clock frequency. As an example, consider an architecture operating at 1 THz sample rate and clocked at about 1 GHz. For an architecture using $N = 1024$ subbands, the DFT computation will be fully parallel, i.e, that block takes all 1024 inputs of the DFT every cycle. This means that each operation in the DFT (FFT) can be simplified. For example, the twiddle factor multipliers only have to take on a single coefficient value, and, hence, can be optimized for that case [25]. On the other hand, a design with, say, $N = 16384$, may have a lower total computational complexity, counting multiplications, but since each complex multiplier now will have to take on 16 different coefficient values (since the input data is distributed over 16 clock cycles), the more complex reconfigurable operators may lead to that the first choice is better, despite its higher total complexity in terms of number of operations. The filters will have a similar implementation trade-off with the additional aspect that if the filters process more than one sample per clock cycle, the computational complexity can be reduced even further by utilizing redundant computations.

A goal here is thus to investigate these trade-offs between parallelism and general/dedicated operations and to derive the optimal parallelism for a given mitigation algorithm and transmission quality.

3.1.4 Optical-Channel Modeling

An important aspect when deriving efficient digital mitigation algorithms is to have appropriate models of the errors that emanate from the optical channels. For example, for chromatic dispersion, the phase distortion frequency response $\exp(-jK(\omega T)^2)$ corresponds to the first nonlinear term in a Taylor series expansion of a nonlinear phase response. The term $\exp(-jK(\omega T)^2)$ dominates [4], and it therefore suffices to use this as the chromatic dispersion model for sparse constellation diagrams and modest bit error rates. However, with increasing constellation diagram density and reduced bit error rates, one has to use refined models. Further, to model fiber nonlinearities, one needs an appropriate digital model of a nonlinear Schrdinger equation [14], whereas appropriate linear models can be used for the polarization mode dispersion [1, 14] and I/Q mismatches [15–17]. In all cases, one should not use more sophisticated models than necessary, as that may lead to an unnecessarily high computational complexity. For example, as mentioned before, one may use a general Volterra series to model the nonlinearities [18], but the inverse of such a series comes with a high computational complexity. To reduce the complexity, we aim to use appropriate parallel LNL systems, in particular solutions based on the scheme in [20] which combines parallel LNL systems with multirate techniques to also enable compensation of undersampled nonlinearities. The overall goal of this part of the project is to explore the model and design space versus mitigation algorithm complexity, and derive knowledge of their interaction. To support this part of the project, we aim to collaborate with research groups from the optical domain who can provide real data (see Section 6).

3.2 Time Plan and Dissemination

The project is to support one PhD student and supervision. Natural milestones are therefore a licentiate degree after three years and a PhD degree after five years. The results will also be published in prestigious journals and conferences. For the licentiate degree, the focus in the project will be on massively parallel mitigation algorithms for chromatic dispersion and modeling as outlined in Sections 3.1.1 and 3.1.4, respectively. For the PhD degree, the results will then be extended to incorporate other types of errors, as mentioned in the beginning of Section 3.1, and to incorporate elastic schemes and architectures as outlined in Sections 3.1.2 and 3.1.3, respectively.

3.3 Management

The principal investigator (PI) of the project is Prof. Håkan Johansson at the Division of Communication Systems which belongs to the Dept. of Electrical Engineering at Linkping University. The PI has a long experience and well documented expertise in the design of efficient signal processing systems. The co-PI is Docent Oscar Gustafsson at the Division of Computer Engineering at the same department. He has a long experience and well documented expertise in the mapping of DSP algorithms to hardware architectures (algorithm/hardware co-design). We also aim to collaborate with research groups from the optical domain who can provide real data (see Section 6). The funding applied for is to support the PI (20%), co-PI (10%), and one Ph.D. student (90%).

4 Significance

The expected scientific result is knowledge in the design of energy-efficient massively parallel subband-based mitigation algorithms. The focus is on the mitigation of errors that inevitably appear in optical communication channels. Thereby, as discussed in Sections 1 and 2, the expected results constitute enablers for the multi-Tb/s optical channels required for the future Internet traffic. However, such mitigation algorithms are of interest in general as there is a continuously increasing demand for higher data rates and more energy-efficient signal processing techniques. The expected results are therefore important in general for energy-efficient and high-capacity signal processing and communication systems. This is of interest for the academia as well as companies that produce equipment for communication systems.

5 Preliminary Results

As explained in more detail in Section 3, the proposed project is inspired by our recent work on the design of high-order filters and many-channel filter banks with few optimization parameters and efficient online adaptable DSP algorithms [21–23]. Our recent works on chromatic dispersion mitigation [6], I/Q balancing [16], and linearization [20] are also sources of inspiration.

6 Co-Operation

During the project, we aim to collaborate with research groups from the optical side. Internationally, we have recently initiated a co-operation with the University College London (Dr. Seb J. Savory) which has resulted in a joint publication [6]. We intend to strengthen the co-operation through this project. Nationally, we have initiated discussions with Chalmers (Prof. Peter Andrekson et al), and we intend to intensify the discussions during the project, aiming at future co-operation. These collaborations will in particular be fruitful for the optical-channel modeling part of the project.

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[6] A. Eghbali, H. Johansson, O. Gustafsson, and S. J. Savory, "Optimal least-squares FIR digital filters for compensation of chromatic dispersion in digital coherent optical receivers," *IEEE/OSA J. Lightwave Technology*, vol. 32, no. 8, pp. 1449–1456, Apr. 2014.

[7] A. K. M. Pillai and H. Johansson, "A sub-band based reconstructor for M-channel time-interleaved ADCs with missing samples," in *Proc. IEEE Int. Conf. Acoustics, Speech, Signal Processing*, Florence, Italy, May 2014.

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[16] H. Johansson, *Methods and apparatuses for compensation of I/Q imbalance*. United States Patent 8588336, Nov. 2013.

[17] ——, “Relations between zero-IF receiver I/Q and TI-ADC channel mismatches,” *IEEE Trans. Signal Processing*, vol. 62, no. 13, pp. 3403–3414, July 2014.

[18] J. Tsimbinos, *Identification and Compensation of Nonlinear Distortion*. Diss., University of South Australia, 1995.

[19] N. Björsell, *Modeling Analog to Digital Converters at Radio Frequency*. Diss. no. 4523, Royal Institute of Technology, Stockholm, Sweden, 2007.

[20] H. Johansson, *Methods and apparatuses for estimation and compensation of nonlinearity errors*. Japanese Patent 5215477, July 2013.

[21] A. Eghbali and H. Johansson, “On efficient design of high-order filters with applications to filter banks and transmultiplexers with large number of channels,” *IEEE Trans. Signal Processing*, vol. 62, no. 6, pp. 1198–1209, Mar. 2014.

[22] H. Johansson and F. Harris, “Polyphase decomposition of digital fractional-delay filters,” *IEEE Signal Processing Lett.*, vol. 22, no. 8, pp. 1021–1025, Aug. 2015.

[23] H. Johansson and A. Eghbali, “Two polynomial FIR filter structures with variable fractional delay and phase shift,” *IEEE Trans. Circuits Syst. I: Regular Papers, Special Issue on ISCAS-2013, Invited Paper*, vol. 61, no. 5, pp. 1355–1365, May 2014.

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[25] O. Gustafsson, “Lower bounds for constant multiplication problems,” *IEEE Trans. Circuits Syst. II*, vol. 54, no. 11, pp. 974–978, Nov. 2007.

Interdisciplinarity

My application is interdisciplinary

☐

An interdisciplinary research project is defined in this call for proposals as a project that can not be completed without knowledge, methods, terminology, data and researchers from more than one of the Swedish Research Councils subject areas; Medicine and health, Natural and engineering sciences, Humanities and social sciences and Educational sciences. If your research project is interdisciplinary according to this definition, you indicate and explain this here.

Click here for more information

Scientific report

Scientific report/Account for scientific activities of previous project

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Budget and research resources

Project staff

Describe the staff that will be working in the project and the salary that is applied for in the project budget. Enter the full amount, not in thousands SEK.

Participating researchers that accept an invitation to participate in the application will be displayed automatically under Dedicated time for this project. Note that it will take a few minutes before the information is updated, and that it might be necessary for the project leader to close and reopen the form.

Dedicated time for this project

	Role in the project	Name	Percent of full time
1	Applicant	Håkan Johansson	20
2	Participating researcher	Oscar Gustafsson	10
3	Other personnel without doctoral degree	PhD student	90

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	2019	Total
1	Applicant	Håkan Johansson	20	257,000	262,000	267,000	273,000	1,059,000
2	Participating researcher	Oscar Gustafsson	10	110,000	112,000	115,000	117,000	454,000
3	Other personnel without doctoral degree	PhD student	90	479,000	489,000	499,000	509,000	1,976,000
	Total			846,000	863,000	881,000	899,000	3,489,000

Other costs

Describe the other project costs for which you apply from the Swedish Research Council. Enter the full amount, not in thousands SEK.

Premises

Type of premises	2016	2017	2018	2019

Running Costs

	Running Cost	Description	2016	2017	2018	2019	Total
1	Travels		70,000	70,000	70,000	70,000	280,000
2	Equipment (computers etc.)		30,000	30,000	30,000	30,000	120,000
	Total		100,000	100,000	100,000	100,000	400,000

Depreciation costs

Depreciation cost	Description	2016	2017	2018	2019

Total project cost

Below you can see a summary of the costs in your budget, which are the costs that you apply for from the Swedish Research Council. Indirect costs are entered separately into the table.

Under Other costs you can enter which costs, aside from the ones you apply for from the Swedish Research Council, that the project includes. Add the full amounts, not in thousands of SEK.

The subtotal plus indirect costs are the total per year that you apply for.

Total budget

Specified costs	2016	2017	2018	2019	Total, applied	Other costs	Total cost
Salaries including social fees	846,000	863,000	881,000	899,000	3,489,000		3,489,000
Running costs	100,000	100,000	100,000	100,000	400,000		400,000
Depreciation costs					0		0
Premises					0		0
Subtotal	946,000	963,000	981,000	999,000	3,889,000	0	3,889,000
Indirect costs	331,000	337,000	343,000	349,000	1,360,000		1,360,000
Total project cost	1,277,000	1,300,000	1,324,000	1,348,000	5,249,000	0	5,249,000

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

The funding applied for is to support the PI (20%), co-PI (10%), and 1 Ph.D. student (90%), and to cover conference, publication, and equipment costs. We have assumed an annual salary increase of 2%.

The proposed project is not supported by any other financial means.

Other funding

Describe your other project funding for the project period (applied for or granted) aside from that which you apply for from the Swedish Research Council. Write the whole sum, not thousands of SEK.

Other funding for this project

Funder	Applicant/project leader	Type of grant	Reg no or equiv.	2016	2017	2018	2019

CV and publications

CV

Håkan Johansson's Curriculum Vitae

Prof. Johansson's research encompasses theory and design of efficient signal processing systems, mainly for communication applications. During the past decade, Prof. Johansson has developed many different signal processing algorithms for various purposes, including filtering, sampling rate conversion, signal reconstruction, and parameter estimation. He has developed new estimation and compensation algorithms for errors in analog circuits such as compensation of mismatch errors in time-interleaved analog-to-digital converters and mixers. He is one of the founders of the company Signal Processing Devices Sweden AB that sells this type of advanced signal processing.

Degrees and Employments

1. M.Sc. degree in Computer Science and Engineering (Civ.ing, D-linjen), 1995.
2. Ph.D. (Tekn. Dr.) degree in Electronics Systems (Elektroniksystem), 1998.
   Title: Synthesis and realization of high-speed recursive digital filters
   Supervisor: Prof. Lars Wanhammar
3. Post doctoral position at Tampere University of Technology, 1998-1999.
4. Docent degree in Electronics Systems, Sept. 2001.
5. Current permanent position (100%): Prof. at Dept. EE Linköping University, from July 2004.
6. Previous positions:
   - Part-time positions: System developer at the company Signal Processing Devices Sweden AB, different periods, 2007-2013.
   - Ass. Prof. (universitetslektor) at Dept. EE Linköping University, July 1999-June 2004.
   - Post doctoral position at Tampere University of Technology, 1998-1999.
   - Ph. D. student at Dept. EE Linköping University, 1995-1998.
7. Interruption in research
   - A total of three years work in industry 2007-2013.
   - Parental leave 75% during 3 months november 2004-januari 2005 and 50% during 3 months february-may 2007.
8. Main supervisor of 6 graduated Ph.D. students
   - Muhammad Abbas, February 2012, - Zaka Ullah Sheikh, March 2012
   - Amir Eghbali, December 2010, - Mattias Olsson, June 2008
   - Linnea Rosenbaum, June 2007, - Per Löwenborg, December 2002

Selected previous research grants (Approximate USD numbers based on 1 USD = 8 SEK)

Principle Investigator (PI):

- Swedish Research Council, "Modulation-sequence based analog-to-digital conversion", 2010-2012. 280,000 USD.
- Swedish Research Council, "Efficient and flexible digital signal processing algorithms", 2006-2008. 240,000 USD.

Co-PI:

- Swedish Foundation for Strategic Research, grant holder Erik. G. Larsson, Div. of Communication Systems, Dept. of EE, LiU, "Algorithms and architectures for baseband signal processing", 2008-2011. In total 1,040,000 USD, Prof. Johansson's part 190,000 USD.
- The Swedish Defence Materiel Administration (FMV, Program TAIS), "Components and signal processing for energy starved microwave sensors", cooperation between Chalmers (grant holder Staffan Rudner), LiU, FOI, and SAAB Microwave Systems, 2006-2009. In total 1,250,000 USD, Prof. Johansson's part 305,000 USD.
- Swedish Research Council, grant holder Christer Svensson, Div. of Electronic Devices, Dept. of EE, LiU, "Direct RF sampling for flexible radio architectures", 2006-2008. In total 560,000 USD, Prof. Johansson's part 200,000 USD.

Publications

- 4 books
- 61 international journal papers (3 invited).
- 122 international conference papers (3 invited).
- 13 national conference papers.
- 4 book chapters (invited)

Patents

- 7 patents (plus 2 pending)

Awards

- Co-author of best paper in *J. Circuits, Syst., Comp., Special Issue on Frequency-Response Masking Technique*, 2003.
- Co-author of best paper at *IEEE Nordic Signal Processing Symp*. 2002.
- Co-author of best student paper at *IEEE Midwest Symp*. 1999.

Editorial commitments

- Associate Editor of IEEE Trans. on Circuits and Systems-I, 2008-2009, and 2014-2015.
- Area Editor of the Elsevier J. Digital Signal Processing, since 2013
- Associate Editor of IEEE Trans. Signal Processing, 2006-2008.
- Associate Editor of IEEE Signal Processing Letters, 2004-2007.
- Associate Editor of IEEE Trans. on Circuits and Systems-II, 2000-2001 and 2007.

Award committee commitments

Committee member for the selection of the IEEE Circuits and Systems Society Guillemin-Cauer and Darlington best paper awards, 2011-2013.

Selected conference program committees

- Member of the ComSoc Signal Processing for Communications and Electronics Technical Committee (SPCE TC), since 2014.
- Member of IEEE Int. Symp. Circuits Syst. (ISCAS), DSP track committee, since 2000.
- Member of the Technical Program Committee of the IEEE Wireless Communications and Networking Conference (WCNC), 2013-2014.
- Member of the Technical Program Committee of the IEEE Global Communications Conference (GLOBECOM), 2009-2015.
- Member of the Technical Program Committee of the IEEE International Conference on Communications (ICC), 2011-2013, 2015.
- Member of the Program Committee of the International Symposium on Image and Signal Processing and Analysis (ISPA), 2007, 2009, 2012, 2015.
- Technical Program Committee Reviewer for the 2012 IEEE Symposium on Industrial Electronics and Applications (ISIEA), 2012.
- Member of the Technical Program Committee of the First IEEE International Conference on Communications in China: Signal Processing for Communications (ICCC'12 - SPC), 2012.
- Member of the Technical Program Committee of the Signal Processing and Applications (SPA) track of Mosharaka International Conference on Communications and Signal Processing (MIC-CSP), 2011, 2012.
- Member of the Technical Program Committee for I-WASP 2011, International Workshop on Applications of Signal Processing (I-WASP 2011), 2011.
- Member of the Technical Program Committee of the 10th International Symposium on Communications and Information Technologies (ISCIT), 2010.
- Track co-chair for the IEEE International Conference on Electronics, Circuits, and Systems (ISECS), 2008.
- Member of the Technical Program Committee of the EURASIP European Conference on Signal Processing (EUSIPCO) 2008.
- Member of the Technical Committee of the 18th European Conference on Circuit Theory and Design (ECCTD), 2007.

Opponent/evaluator/expert commitments

- 20 thesis opponent/evaluator/reviewer assignments, 2000-2013.
- Reviewer for the Italian Research and University Evaluation Agency (ANVUR), Sept. 2012- Feb. 2013. "Evaluation of the Italian research system for the period 2004-2010".

Referee commitments

- Reviewer of more than 200 papers for international journals during 2000-2015.
- Responsible of review processes (40 papers) for IEEE Int. Symp. Circuits Syst., 2001–2006.
- Reviewer of more than 100 papers for international conferences during 2000-2015.

Teaching

- Undergraduate courses (Linköping University):
  Analog Circuits, Analog Filters, Circuit Theory, Linear Systems, Digital Filters, Signal Theory
- Graduate courses (Linköping University):
  Multirate Digital Signal Processing, Wave Digital Filters

Development of course books

Co-author of the book Digital Filters, 448–674 pages, 1997–2013, (7 editions).
Author of the book Discrete-Time Systems, 367 pages, 2007.
Author of the book Tidsdiskreta System, 316 pages, 2001–2003 (3 editions).
Co-author of the book Analoga Filter, 222–370 pages, 1999–2003 (5 editions).

Supervision of final projects

About 40 final projects at Master and Bachelor levels in 1997-2014.

Entrepreneurial achievements

- Signal Processing Devices Sweden AB secures EUR 3 Million from SEB Företagsinvest, the venture capital arm of Skandinaviska Enskilda Banken, 2007.
- Winner of VINNOVA's competition Vinn Nu 2004.
- Cofounder of the company Signal Processing Devices Sweden AB, 2004.

CURRICULUM VITAE

OSCAR GUSTAFSSON

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			`www.da.isy.liu.se`

Publications:	`http://scholar.google.com/citations?user=YIFravQAAAAJ`		

REQUIRED INFORMATION

1. M.Sc. (Civilingenjör) in Applied Physics and Electrical Engineering, Linköping University, Sweden. April 1998.
2. Ph.D. in Electronics Systems, Linköping University, Sweden. Sept. 2003
3. –
4. Docent in Electronics Systems, Linköping University, Sweden. April 2008
5. Associate Professor/Senior Lecturer (universitetslektor), July 2009 – , 45% research, 30% administration, 25% teaching
6. Assistant professor (forskarassistent), Oct. 2003 – June 2009
7. Jan. 2007 – July 2007 (part time, about three months in total), Feb. 2003 – Oct. 2003 (part time, about five months in total)
8. Examined PhD students: Kenny Johansson, Oct. 2008, Anton Blad, Sept. 2011, Fahad Qureshi, Mar. 2012. Hosted post-doc: Mario Garrido, June 2010–June 2012, Kevin Cushon, March 2014–Aug. 2014

EDUCATION

April 2008	Docent (equiv. to Associate Professor) in Electronics Systems	Linköping University, Sweden
April 1998 – Sept. 2003	Ph.D. in Electronics Systems	Linköping University, Sweden
Sept. 1995 – April 1996	Exchange student (M.Sc. in Digital Systems Eng.)	Heriot-Watt University, Edinburgh, United Kingdom
Sept. 1992 – April 1998	M.Sc. (Civilingenjör) in Applied Physics and Electrical Engineering	Linköping University, Sweden

APPOINTMENTS

July 2014 –	Head (Avdelningschef) of the Division of Computer Engineering, Linköping University
Jan. 2012 – Dec. 2014	Vice head (Pro-prefekt) of the Department of Electrical Engineering, Linköping University
Sept. 2009 – June 2014	Head (Avdelningschef) of the Division of Electronics Systems, Linköping University
July 2009 –	Associate Professor/Senior Lecturer (Universitetslektor), Linköping University
July 2009 – Aug. 2009	Guest researcher, Nanyang Technological University, Singapore
Oct. 2003 – June 2009	Assistant Professor (Forskarassistent), Linköping University
Jan. 2007 – July 2007	Paternal leave, (part time, about three months in total)
Feb. 2003 – Oct. 2003	Paternal leave, (part time, about five months in total)
April 1998 – Sept. 2003	Ph.D. Student, Linköping University

RESEARCH INTERESTS

- Design and implementation of DSP and communication algorithms
- Digital arithmetic
- Optimization for electrical engineering

RESEARCH FUNDING

- Energy efficient arithmetic, Research associate (forskarassistent) grant, Vetenskapsrådet, 2004–2007, 810 kSEK/y.
- Algorithm-hardware co-design for memory and communication dominated applications, project grant, Vetenskapsrådet, 2007–2009, 675 kSEK/y
- Practical algorithms for highly efficient cooperative transmission in wireless networks, Vinnova, 2008/07–2011/06, 1500 kSEK/y (as Co-PI)
- Contract research, A2B Electronics AB, 2011, 200 kSEK
- Statistical signal processing for communication receivers, project grant, Vetenskapsrådet, 2009–2011, avg. 1500 kSEK/y (as Co-PI)
- Techniques for nonlinear digital-to-analog conversion, project grant, Vetenskapsrådet, 2009–2011, avg. 875 kSEK/y
- Funding for hosting a post-doctoral student, ELLIIT (LIU), 2010+2011, 400 + 400 kSEK
- Algorithm-hardware co-design for FPGAs, project grant, CENIIT (LiU), 2007–2012, 475 kSEK/y
- Techniques for nonlinear digital-to-analog converters, project grant, Vetenskapsrådet, 2010–2012, avg. 788 kSEK/y
- Career contract, LiU, 2009–2013, 525 kSEK/y (1100 kSEK for 2013)
- Techniques for on-board digital signal processing, European Space Agency, 25 kEUR, 2013

SCIENTIFIC OUTPUT

- 4 book chapters
- 26 journal papers
- 124 papers in international conferences
- 1 patent application
- 1 publicly released software package

VOLUNTEER ACTIVITIES

- Senior Member of IEEE
- Member of IEICE
- Associate editor for IEEE Transactions on Circuits and Systems Part II: Express Briefs 2010–2013, Integration, the VLSI Journal, 05/2011–
- Guest editor of Journal of Electrical and Computer Engineering special issue on “Hardware Implementation of Digital Signal Processing Algorithms”
- Member of IEEE Circuits and Systems VLSI Systems and Applications (VSA) Technical Committee, 5/07–, and Digital Signal Processing (DSP) Technical Committee 10/07–
- Treasurer of Sweden section of IEEE Solid-State Circuits Society 2009–2012
- TPC co-chair: PrimeAsia 2010.
- Finance chair: ECCTD 2011
- Special session chair: ECCTD 2015
- Track chair: Asilomar 2008, CrownCom 2010, Eusipco 2010, 2015
- Student paper contest chair: Asilomar 2011
- International coordinator: ISCAS 2012
- TPC member: Norchip 2006, 2009, 2011, ISCAS 2008–, PATMOS 2008–, PrimeAsia 2009, ICGCS 2010, ICECS 2010, ICCSP 2011, Eusipco 2011, INMIC 2011
- Student paper contest jury member: Asilomar 2010
- Editor for the Proceedings of National Conference on Radio Sciences (RVK), 2005
- Organizer of special conference session: CrownCom 2010
- Co-organizer of special conference session: ISCAS 2005
- Conference session chair: ISCAS 2005, 2008–2013, 2015, Norchip 2006, Asilomar 2008, CrownCom 2010, ECCTD 2011
- Reviewer of around 130 papers for 32 different international journals and regular reviewer for the major circuits and systems conferences: ISCAS, ICECS, ECCTD, etc.

Publication list

Håkan Johansson's List of Publications

Number of citations taken from Google Scholar 2015-03-28.
(http://scholar.google.se/citations?user=gHVEbL4AAAAJ&hl=sv)

FIVE MOST CITED PAPERS

1. H. Johansson and P. Löwenborg, "Reconstruction of nonuniformly sampled bandlimited signals by means of digital fractional delay filters," *IEEE Trans. Signal Processing*, vol. 50, no. 11, pp. 2757–2767, Nov. 2002. Number of citations: 143
2. H. Johansson and P. Löwenborg, "On the design of adjustable fractional delay FIR filters," *IEEE Trans. Circuits Syst. II*, vol. 50, no. 4, pp. 164–169, Apr. 2003. Number of citations: 92
3. C. Vogel and H. Johansson, "Time-interleaved analog-to-digital converters: Status and future directions," in *Proc. IEEE Int. Symp. Circuits Syst.*, Kos, Greece, May 21–24, 2006. Number of citations: 73
4. P. Löwenborg, H. Johansson, and L. Wanhammar, "Two-channel digital and hybrid analog/digital multirate filter banks with very low complexity analysis or synthesis filters," *IEEE Trans. Circuits Syst. II*, vol. 50, no. 7, pp. 355–367, July 2003. Number of citations: 59
5. H. Johansson and P. Löwenborg, "Reconstruction of nonuniformly sampled bandlimited signals by means of time-varying discrete-time FIR filters," *EURASIP J. Applied Signal Processing – Special Issue on Frames and Overcomplete Representations in Signal Processing, Communications, and Information Theory*, vol. 2006, Article ID 64185, 18 pages, 2006. Number of citations: 54

* Five most important publications for the project

PEER-REVIEWED JOURNAL PAPERS, 2007-2015

[42] Y. Wang, H Xu, H. Johansson, Z. Sun, and J. J. Wikner, "Digital estimation and compensation method for nonlinearity mismatches in time-interleaved analog-to-digital converters", *Digital Signal Processsing (Elsevier)*, accepted. Number of citations: 0

[41] Y. Wang, H. Johansson, H. Xu, and Z. Sun, "Joint blind calibration for mixed mismatches in two-channel time-interleaved ADCs," *IEEE Trans. Circuits Syst. I - Regular Papers*, accepted. Number of citations: 0

[40] A. K. M. Pillai and H. Johansson, "Prefilter-based reconfigurable reconstructor for time-interleaved ADCs with missing samples," *IEEE Trans. Circuits Syst. II - Express Briefs*, accepted. Number of citations: 0

[39] H. Johansson and H. Göckler, "Two-stage based polyphase structures for arbitrary-integer sampling rate conversion," *IEEE Trans. Circuits Syst. II - Express Briefs*, accepted. Number of citations: 0

[38] A. Eghbali and H. Johansson, "Design of modulated filter banks and transmultiplexers with unified initial solutions and very few unknown parameters," *IEEE Trans. Circuits Syst. II - Express Briefs*, accepted. Number of citations: 0

[37]* H. Johansson and F. Harris, "Polyphase decomposition of digital fractional-delay filters," *IEEE Signal Processing Lett.*, vol. 22, no 8, pp. 1021–1025, Aug. 2015. Number of citations: 0

[36] Y. Wang, H. Johansson, and H. Xu, "Adaptive background estimation for static nonlinearity mismatches in two-channel TIADCs," *IEEE Trans. Circuits Syst. II - Express Briefs*, vol. 62, no. 3, 226–230, Mar. 2015. Number of citations: 0

[35]* H. Johansson, "Relations between zero-IF receiver I/Q and TI-ADC channel mismatches," *IEEE Trans. Signal Processing*, vol. 62, no. 13, 3403–3414, July 2014. Number of citations: 1

[34] H. Johansson and A. Eghbali, "Add-equalize structures for linear-phase Nyquist FIR filter interpolators and decimators," *IEEE Trans. Circuits Syst. I: Regular Papers*, vol. 61, no. 6, pp. 1766–1777, June 2014. Number of citations: 2

[33] H. Johansson and A. Eghbali, "Two polynomial FIR filter structures with variable fractional delay and phase shift," *IEEE Trans. Circuits Syst. I: Regular Papers, Special Issue on ISCAS-2013, Invited Paper*, vol. 61, no. 5, pp. 1355–1365, May 2014. Number of citations: 0

[32]* A. Eghbali, H. Johansson, O. Gustafsson, and S. J. Savory, "Optimal least-squares FIR digital filters for compensation of chromatic dispersion in digital coherent optical receivers," *IEEE/OSA J. Lightwave Technology*, vol 32, no. 8, pp. 1449–1456, Apr. 15, 2014. Number of citations: 5

[31] W. J. Xu, Y. J. Yu, and H. Johansson, "Improved filter bank approach for the design of variable bandedge and fractional delay filters," *IEEE Trans. Circuits Syst. I: Regular Papers*, vol. 61, no. 3, pp. 764–777, Mar. 2014. Number of citations: 0

[30] A. Eghbali, T. Saramäki, and H. Johansson, "Conditions for Lth-band filters of order $2N$ as cascades of identical linear-phase FIR spectral factors of order N," *Signal Processing*, vol. 97, pp. 1–8, Apr. 2014.

Number of citations: 0

[29]* A. Eghbali and H. Johansson, “On efficient design of high-order filters with applications to filter banks and transmultiplexers with large number of channels,” *IEEE Trans. Signal Processing*, vol. 62, no. 5, pp. 1198-1209, Mar. 2014. Number of citations: 2

[28] A. Eghbali and H. Johansson, “A class of reconfigurable and low-complexity two-stage Nyquist filters,” *Signal Processing*, vol. 96, pp. 164–172, Mar. 2014. Number of citations: 1

[27] A. K. M. Pillai and H. Johansson, “Efficient signal reconstruction scheme for *M*-channel time-interleaved ADCs” *J. Analog Integrated Circuits Signal Processing, Special Issue on IEEE NEWCAS 2012*, vol. 77, no. 2, pp. 113–122, Nov. 2013. *Invited Paper.* Number of citations: 0

[26] H. Johansson, “On FIR filter approximation of fractional-order differentiators and integrators,” *IEEE J. Emerging Selected Topics Circuits Syst.*, vol. 3, no. 3, pp. 404–415, Sept. 2013. Number of citations: 2

[25] M. Abbas, O. Gustafsson, and H. Johansson, “On the fixed-point implementation of fractional-delay filters based on the Farrow structure,“ *IEEE Trans. Circuits Syst. I - Regular Papers*, vol. 60, no. 4, pp. 926–937, Apr. 2013. Number of citations: 8

[24] A. Eghbali, H. Johansson, T. Saramäki, “A method for the design of Farrow-structure based variable fractional-delay FIR filters,” *Signal Processing*, vol. 93, no. 5, pp. 1341–1348, May 2013. Number of citations: 5

[23] H. Johansson and E. Hermanowicz, “Two-rate based low-complexity variable fractional-delay FIR filter structures,” *IEEE Trans. Circuits Syst. I: Regular Papers*, vol. 60, no. 1, pp. 136–149, Jan. 2013. Number of citations: 10

[22] A. K. M. Pillai and H. Johansson, “Two-rate based low-complexity time-varying discrete-time FIR reconstructors for two-periodic nonuniformly sampled signals” *Sampling Theory in Signal and Image Processing - Special Issue on SampTA 2011*, vol. 11, no. 2-3, pp. 195-220, 2012. Number of citations: 2

[21] Z. U. Sheikh and H. Johansson, “Efficient wide-band FIR LTI systems derived via multi-rate techniques and sparse bandpass filters“, *IEEE Trans. Signal Processing*, vol. 60, no. 7, pp. 3859–3863, July 2012. Number of citations: 8

[20] H. Johansson, “Fractional-delay and supersymmetric *M*th-band linear-phase FIR filters utilizing partially symmetric and antisymmetric impulse responses“, *IEEE Trans. Circuits Syst. II - Express Briefs*, vol. 59, no. 6, pp. 366–370, June 2012. Number of citations: 3

[19] A. Eghbali, H. Johansson, and P. Löwenborg, “A class of multimode transmultiplexers based on the Farrow structure,” *Circuits Syst. Signal Processing*, vol. 31, no. 3, pp. 961–985, June 2012. Number of citations: 9

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Dissertation title (en)
Synthesis and Realization of High-Speed Recursive Digital Filters

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Dissertation title (en)
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Johansson, Håkan has not added any publications to the application.

Publications

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Gustafsson, Oscar has not added any publications to the application.

Register

Terms and conditions

The application must be signed by the applicant as well as the authorised representative of the administrating organisation. The representative is normally the department head of the institution where the research is to be conducted, but may in some instances be e.g. the vice-chancellor. This is specified in the call for proposals.

The signature*from the applicant*confirms that:

- the information in the application is correct and according to the instructions form the Swedish Research Council
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- that the necessary permits and approvals are in place at the start of the project e.g. regarding ethical review.

The signature *from the administrating organisation* confirms that:

- the research, employment and equipment indicated will be accommodated in the institution during the time, and to the extent, described in the application
- the institution approves the cost-estimate in the application
- the research is conducted according to Swedish legislation.

The above-mentioned points must have been discussed between the parties before the representative of the administrating organisation approves and signs the application.

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