Application

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Descriptive data

Project info

Project title (Swedish)*

Smarta sensorer och kommunikation med energiinsamling

Project title (English)*

Smart Sensing and Communications with Energy Harvesting

Abstract (English)*

A wireless sensor network (WSN) is a collection of sensors which sense their environment, collect information and communicate this information to each other or to a decision center wirelessly. WSNs play important roles in a wide range of applications including environmental monitoring, surveillance, process monitoring, body area networks and smart homes. A growing concern in today's sensing systems is the efficient usage of energy resources. In that respect, solutions that consider energy harvesting (EH) offer a promising perspective. Sensors with EH capabilities use the other available energy sources, such as solar power or mechanical vibrations, instead of completely relying on a fixed battery or the power from the grid.

EH capabilities bring new engineering challenges for the design of sensing and communication strategies. When the energy to be harvested comes from renewable sources, (predictable yet still) unreliable characteristics of these sources is the key issue.

Recently, there has been a significant effort to understand the information transfer capabilities of sensing and communications systems with EH capabilities. Here the mainstream approach is to focus on the difficulties regarding the reliable communications. These works typically consider an information-theoretic framework with the rate maximization as the performance criterion. This line of work is important for understanding the fundamental limits regarding communications with EH systems, yet it cannot adequately exploit the interactions between sensing and communications. An example of this interaction is the trade-off between how often the measurements should be made and how often they can be sent. This project will address these issues by considering sensing and communications in a joint framework.

The main aim of the project is to provide guidelines about optimal sensing and communication strategies for systems relying on EH sensors. We will consider a unified framework that jointly optimizes sensing and communication strategies. The questions of ``when and how to make measurements, i.e. sense'' and ``when and how to send, i.e. communicate'' will be treated jointly. The underlying performance criteria is accurate reconstruction of the unknown field, i.e. estimating the unknown values of interest, such as humidity over an entire farm area, as accurately as possible. For data transmission, low-complexity signal processing techniques (linear precoding, power allocation) will be emphasized. Delay constraints, energy costs of sensing, battery size constraints and battery imperfections will be important ingredients of our framework. We will answer questions such as ``for a given energy reliability of EH source, when, where, and with what accuracy the samples should be taken?'', ``how reliable should the energy harvesting sources be to achieve a target distortion for field recovery?''.

We will first consider the scenarios where the energy that can be provided by the renewable energy sources can be predicted accurately. Then we will move onto more challenging scenarios where only statistical knowledge about the energy sources is available. We will also do measurements to characterize the energy availability from renewable sources for low power devices. This data will be used to evaluate our assumptions about energy arrival processes and the performance of our proposed solutions.

With its unified framework that considers sensing and communication aspects jointly, its emphasis on low-complexity solutions and the complementary measurements for characterizing the energy availability, our project will provide us comprehensive engineering insights about energy harvesting systems that cannot be provided by the current approaches. These results will give us guidelines for our decisions about when and how to include renewable energy sources in our future sensing systems.

Popular scientific description (Swedish)*

Idag är många bekvämligheter i vårt liv beroende av olika sorters autonoma sensorer. Exempel är t.ex. parkerings sensorer i bilar eller fuktighetssensorer som övervakar den växande grödans status. Sensorsystem spelar en viktig roll i en stor mängd tillämpningar inklusive miljöövervakning, bevakning, medicinska tillämningar och i olika smarta hem scenarier.

Ett attraktivt sätt att driva dessa sensorer är med hjälp av energiinsamling. Att infånga energi från förnybara energikällor benämns energiinsamling; t.ex. kan man använda solceller för att driva ett system för övervakning av grödor.En stor utmaning för tillämpningar som integrerar förnyelsebar energi i sensorsystemet är osäkerheten i tillgänglighet från energikällan. Som ett exempel vet vi att solen kommer att gå upp i morgon men vi vet inte hur molnigt det kommer att bli. Ett sensorsystem som drivs med en solceller kan därmed ibland ha mycket energi tillgänglig och ibland lite.

Syftet med detta projekt är att utveckla kommunikation och sensorstrategier som erbjuder en funktion som både är tillförlitlig och effektiv även om energikällan är osäker. Vi är specifikt intresserade i "när och hur som man ska mäta, dvs när sensorerna ska vara aktiva" och "när och hur ska man skicka data, dvs när och ska man kommunicera". En av frågeställningarna vi söker svar till är "Hur tillförlitliga måste de förnyelsebara källorna vara för att kunna mäta det okända fältet (t.ex. fuktigheten i grödan) för en given nivå på mätfelet?". Vi kommer att studera avvägningen mellan antalet sensorer och deras noggrannhet, hastigheten med vilken system kommunicerar med och tillförlitligheten i energikällan. Dessa resultat kommer att ge riktlinjer för framtida beslut kring när och hur förnyelsebara källor kan användas i våra framtida sensorsystem.

Project period

Number of project years*

4

Calculated project time*

2016-01-01 - 2019-12-31

Deductible time

Deductible time

Cause	Months

Career age: 30

Career age is a description of the time from your first doctoral degree until the last day of the call. Your career age change if you have deductible time. Your career age is shown in months. For some calls there are restrictions in the career age.

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

2. Teknik > 202. Elektroteknik och elektronik > 20203. Kommunikationssystem

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

Keyword 1*

signal processing

Keyword 2*

energy harvesting

Keyword 3*

sensing

Keyword 4

communications

Keyword 5

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*

There is no ethical considerations related to the project.

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

I. Purpose and Aims

A wireless sensor network (WSN) is a collection of sensors which sense their environment, collect information and communicate this information to each other or to a decision center wirelessly. WSNs play important roles in a wide range of applications including environmental monitoring, surveillance, process monitoring, body area networks and smart homes [1], [2].

A growing concern in today's sensor networks is the efficient usage of energy resources. In that respect, solutions that consider **energy harvesting (EH)** offer a promising perspective. Sensors with EH capabilities use the other available energy sources, such as solar power or mechanical vibrations, instead of completely relying on a fixed battery or the power from the grid. In addition to utilizing energy resources that may otherwise be wasted, EH capabilities offer prolonged battery life-times, eliminates the need for dedicated power cables and offers significant mobility for the nodes in the network [1–3].

Nevertheless, energy harvesting capabilities bring new engineering challenges for the design of sensing and communication strategies. When the energy to be harvested comes from natural sources, (predictable yet still) unreliable characteristics of these sources, i.e. **intermittent nature of the energy supply**, is the key issue.

In a traditional communication scenario, the power that can be used for communication at a given channel usage has a fixed known value. In contrast, for an EH node utilizing an unreliable source, power available for transmission is typically best modeled as a random quantity and depends on the power usage in previous transmissions. In such systems, the transmission strategies have to be re-designed in order to ensure reliable transmission in the whole time frame of interest. For instance, at a given instant, a node relying on energy harvested for its operations may have to choose between increasing the power used in the current transmission to increase reliability at that instant or saving the energy for future upcoming transmissions.

Hence, there has been a significant recent effort to understand the information transfer capabilities of sensing and communications systems with such capabilities. Currently, the mainstream approach is to focus on the difficulties regarding the reliable communication. However, this approach generally ignores that in many scenarios there is an underlying phenomenon observed by the sensors and the ultimate aim of the communication is to efficiently transfer information about this phenomenon. Sensing systems used in environmental monitoring, where sensors are used to reconstruct an unknown multi-dimensional signal (field), such as a humidity or temperature field, are typical examples of such scenarios [1].

Hence the current communications based approaches cannot adequately exploit the interactions between sensing and communication. An example of this interaction is the trade-off between how often the measurements should be made and how often they can be sent. As a result, the mainstream approach cannot answer questions such as when it is better to make measurements as often as possible and risk not being able send all of them or alternatively to make measurements less frequently and be able to send most of them. This project will address these issues by considering sensing and communications in a joint framework.

The main aim of this project is to develop sensing and communication strategies for systems utilizing energy harvesting. The questions of "when and how to make measurements, i.e. sense" and "when and how to send, i.e. communicate" will be treated jointly. The underlying performance criteria is accurate reconstruction of the unknown field, i.e. estimating the unknown values of interest, such as humidity over an entire farming area, as accurately as possible. In particular, the objectives of the project are the joint design of the following

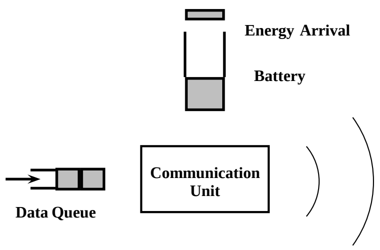
- Sensing strategies (sampling rates, location of sensors, accuracy of the measurements) for EH nodes
- Low-complexity signal processing techniques (linear precoding, power allocation) for communication using EH nodes

Our results will reveal the fundamental limitations brought by using EH sensors. The trade-offs between the reliability of EH sources, the sampling rates and the accuracy of the measurements will be presented. These trade-offs will provide resource allocation, signal processing and communication guidelines for future sensing systems with EH capabilities which cannot be provided by the current approaches.

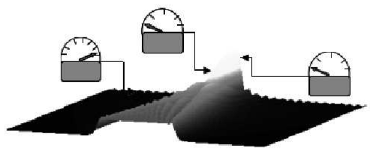
II. Survey of the field

Feasibility of energy harvesting have been investigated and promising results are obtained for various different scenarios, including harvesting energy from solar energy, mechanical energy sources and radio-frequency (RF) energy [1], [2], [4], [5]. For instance, operation of a batteryless wireless sensor utilizing RF energy harvesting is demonstrated [4]. A data rate of 470 kB/s is predicted to be achievable using a solar EH device carried by a pedestrian walking indoors and outdoors [5]. With the advancements in low power electronics, EH technologies became more relevant [3] and commercial businesses promoting EH devices are in the market [6], [7].

In parallel to these promising developments, there has been a significant effort to understand the information transfer capabilities of communication systems with EH capabilities. Here the key issue is the **intermittent nature of the energy supply**. Hence the main aim is to provide reliable and efficient operation in these systems even when the energy supply in unreliable.



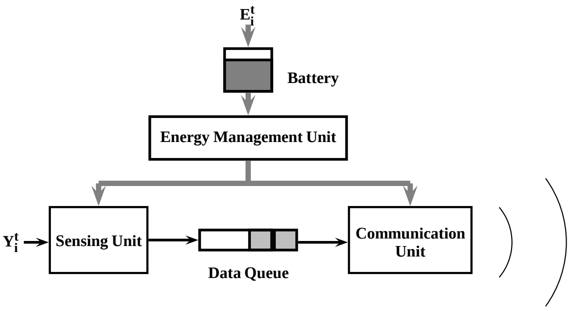
(a) Device with energy harvesting capabilities.



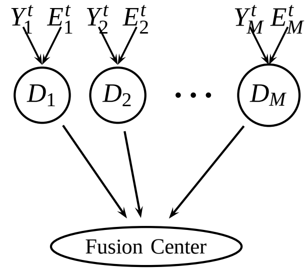
(b) Sensing of the unknown field.

Fig. 1: An energy harvesting device and a sensing system.

Communication Aspects in EH systems: Studies for understanding the limitations of EH systems typically focus on the reliable communications problem. The main EH node model for this problem is shown in Fig. 1a. Here under intermittent available energy constraints, optimal data transmission strategies are developed. An important distinction is the one between the **offline optimization scheme** and the **online optimization scheme** [8]. In the offline (or deterministic) scheme, the profile of the harvested energy is assumed to be known non-causally. On the other hand, in the online (or random) scheme, only statistical knowledge about the energy arrivals is assumed to be available at the time of design. Most of the current works adopt an information-theoretic framework and focus on rate maximization as the performance criteria, see for instance [8–11] and [8], [12] for offline and online schemes, respectively.



(a) Device i with energy harvesting capabilities. In contrast to Fig. 1a both sensing and communication energy costs are accounted for.



(b) Sensor system at time t. D_i: Sensor device i (Model shown in Fig. 2a). E_i^t : Energy Arrival to D_i at time t. Y_i^t: Measurement done by D_i at time t.

Fig. 2: System model for the proposed project.

Sensing Problem: The above mainstream approach that focuses on communications aspects has mostly ignored the ultimate aim of these transmissions: retrieval of information about the underlying phenomena; in particular the **recovery of the unknown field** measured by the sensors. Hence, although these works successfully address issues related to reliable communications, they can only provide limited insights about the fundamental limits of the **inverse problem** at hand.

An illustration of the problem of sensing an unknown field with sensors is provided in Fig. 1b. Here each sensor makes an observation of an unknown field and sends its observation to a fusion (decision) center. An estimate of the whole field is done at the fusion center. The issue is to determine the optimal sensor strategies, i.e. sensor deployment policies and sensing (sampling and source compression) and communication policies at the sensors, so that the field is estimated as accurately as possible at the fusion center. Such sensing scenarios are referred to as “distributed estimation” problems [13].

Previously, works on distributed estimation have successfully provided guidelines for sensing strategies when the sensors have reliable power sources (i.e. without EH constraints), see for instance [13–16]. Here optimal sensing strategies are closely related to the fundamental bounds associated with **inverse problems** and **signal recovery**. The answer to the question of “when/where to do the measurements” is inherently connected to the conditions expressed by the Shannon-Nyquist sampling theorem and its generalizations, and to the recent findings in the area of compressive sampling [17].

Sensing Aspects in EH Systems: Although the works on EH systems mostly focus on reliable communications, a number of recent works have considered sensing related aspects. The problem of parameter estimation, where the unknown field is represented with a scalar number at a given time instant, is considered in [18], [19]. Models where the unknown field is represented as Markov sources are investigated [20], [21]. A number of works on EH systems have focused on the energy costs related to sensing [22], [23]. Sensing issues have also been studied from network utility perspectives [23], [24].

III. Project Description

A. Theory and Methodology

The main aim of this project is to develop sensing and communication strategies for systems utilizing energy harvesting. The main setting of the project is given in Fig. 2.

We will answer questions such as “for a given energy reliability of EH source, when and where the samples should be taken?”, “how reliable should the energy harvesting sources be to achieve a target distortion for field recovery?”, “what is the best strategy to trade the energy availability and the number of sensors: is it better to use a high number of sensors with low energy conversion rates (i.e. cheaper devices) or low number of sensors with high energy conversion rates (i.e. more expensive devices)?”. We arrange our work as follows:

Work Package 1 (WP1): **Offline (deterministic) scheme:** We consider the offline scheme where the energy arrivals are assumed to be known non-causally at the sensor [8–11]. This scheme is suited for scenarios where the energy output can be predicted with high accuracy, such as the energy output of a solar panel depending on the season, time and device characteristics [5]. It also serves as a benchmark showing what levels of performance can be achieved under the optimistic assumption of known energy arrivals. The following specific problems will be addressed jointly:

- Sensing: Development of sampling strategies for field recovery with sensors with EH capabilities. Spatial sampling locations (Task 1), temporal sampling rates (Task 2) and accuracy of the sensor measurements, i.e. quantization policies, (Task 3) will be designed.
- Communication: Design of low complexity power allocation (Task 4) and linear precoding strategies (Task 5) for data transmission with EH sensors. Our investigations will include linear precoding over time, for instance averaging of sensor observations, (Task 5A) and linear precoding over virtual multiple-input multiple-output (MIMO) links through sensor collaboration (Task 5B) [25].

We will first consider the decentralized solutions where the sensors decide using only their own energy arrival knowledge (**WP1.1**), and then move onto the centralized solutions (**WP1.2**) In contrast to mainstream information-theoretic approaches [8–12], we will focus on multi-sensor, hence multi-user scenarios. For field recovery, we will focus on mean-square error or signal-to-noise ratio (SNR) based metrics. We will consider design of strategies over both finite and infinite time horizons. Battery size constraints, battery imperfections and delay constraints will be important ingredients of our work.

The energy cost of sensing (including sampling and compression) vary according to the application and may be at a level comparable with that of radio transmission [22], [26]. Hence we will consider the sensor device model given in Fig. 2a which incorporates the energy expenditures related to the sensing. Using a similar model, Ref. [22] has shown that under queue stability and distortion constraints, the sensing and communication operations can be separately optimized. Whether this observation extends to the scenarios considered in this project will be an important issue we will address.

The correlation between the values of the field will be modeled through the covariance function of the unknown field. Various characteristics of physical fields can be captured using covariance functions; see, for instance, [16], [27] for examples with optical fields.

The answers to the questions we have stated in the beginning of this section will heavily depend on the correlation between the values of the field. For instance, it is inefficient to sample the field values too often in time if the field is highly-correlated temporally and the energy source is unreliable to the extend that only a few of the measured values can be sent reliably over the data link: once these measurement values are put into the data queue, the communication unit will try to send them all of these observations using the valuable energy sources although this data that does not significantly contribute to the estimation of the unknown field.

Although one can utilize the source-channel separation theorem to decouple these problems [28], and make sure that the data in the data queue is independently and identically distributed, this approach has its drawbacks. It assumes the sensor has possibly high-complexity circuitry for source and channel encoding; which may not be possible for simple EH sensors. Moreover, it ignores the energy used for sensing and the encoding operations and the delays incurred by encoding. Motivated by these observations, here we focus on low-complexity analog transmission strategies based on linear precoding [13].

Work Package 2 (WP2): **Online (random) scheme:** The sensing and communications problems described in WP1 will be studied under the online optimization scheme, where the energy arrival process is modeled as a random process [8], [12]. We will first consider the decentralized solutions (where the sensors only know the parameters of their own energy arrival process) (**WP2.1**), and then move onto the centralized solutions (**WP2.2**). To model the energy arrival process, we will consider both the case with independently and identically distributed source model and the Markov source model. We note that the former is a special case of the latter. In addition to the questions in WP1, the following issues are important in the online scheme:

A significant concern is the optimality of threshold policies [20]. In Ref. [20], it is shown that the optimal strategy for a sensor node observing a multi-dimensional Gaussian Markov source is an energy-dependent threshold-based strategy. Whether, such threshold-based strategies are still optimum in multi-sensor environments where the observations of the sensors are spatially/temporally correlated, is not clear. This issue will be addressed in this project.

For additive white Gaussian noise (AWGN) channel, the capacity under online scheme without battery constraints is the same as the capacity of a classical AWGN channel with an average power constraint equal to the average energy harvesting rate [12]. Hence the EH system and the traditional system that is powered from the grid can provide the same data rate as long as the average power values are the same. It is not clear whether this promising observation extends to multi-user scenarios under field recovery constraints. Our project will address this issue.

Battery size constraints significantly affect the structure of the optimal solutions and the analytical tractability. An example is the capacity of the energy harvesting AWGN channel for the case where the battery size goes to infinity [12] and the finite battery size case [29]. In that regard, investigating finite battery size constraints will be particularly important.

Work Package 3 (WP3): **Measurements for Characterizing Energy Availability from Renewable Sources for Low-Power Devices:** Measurements to obtain data for characterizing the energy availability from renewable sources will be done. Here the key issue is to assess the reliability of these sources for *low-power devices*. Although analysis for large scale applications (such as power generation for grid) are done throughly, the number of the works that focus on the energy availability for low-power devices is limited [5].

Our target energy sources include light and radio frequency (RF) energy. Using photo-detectors and RF harvesters (for instance P2110B Powerharvester Receiver [30]), measurements of these sources in use-case scenarios will be done.

Let us consider a scenario that focuses on light energy. By placing photo-detectors in various office environments, we will obtain data to characterize the availability of indoor light energy at Gothenburg. This will give us the fluctuations in the energy availability during an hour, a day or a month. These measurements will complement the existing work, for instance the work in [5] where similar measurements are done in New York. The comparison of this data, for these two cities and also for different times of year, will guide as about how adaptive our optimal energy expenditure strategies should be. This data will allow us to make informed decisions about whether there are global algorithm parameters that should be tuned when the same sensor system is to be deployed in buildings in different cities.

Together with the energy conversion efficiencies, these measurements will give us the fluctuations of the energy that can be provided by renewable sources. This data will be used to evaluate our assumptions about energy arrival processes and the performance of our proposed solutions.

An overview of the methodology for the project: The trade-offs between the system parameters will be studied through optimization problems. Firstly analytical and secondly numerical approaches will be adopted. Our first aim is to gain high level analytical insight to the optimal strategies and the trade-offs between energy reliability, estimation error and delay. Our second aim is to provide low complexity practical strategies.

Lower and upper bounds, and high/low SNR approximations will be used to gain engineering insight to the optimal solutions. Karush-Kuhn-Tucker (KKT) necessary and sufficient conditions, Taylor series expansion of the objective and the constraint functions are among the analytical approaches to be considered whenever applicable. Majorization and Schur-convexity concepts, which has been used in various works with EH constraints, will be important tools [31]. In the case of online schemes, stochastic optimization tools will be utilized [32].

Based on the problem structure, we will consider convex optimization methods or more general nonlinear optimization methods, such as dynamic programming, gradient descent and Newton methods, interior point methods, sequential quadratic programming methods and Gauss-Seidel method based approaches [33]. Developing practical algorithms with reduced complexity that can be implemented in a decentralized manner will be an important concern.

B. Timetable and Implementation

A schedule of the overall work plan is given in Table 1. The results will be communicated through publications on international journals such as IEEE Transactions on Signal Processing or IEEE Transactions on Wireless Communications, and conferences such as IEEE International Conference on Acoustics, Speech and Signal Processing and IEEE International Symposium on Information Theory. These results will also be made publicly accessible through the university's web-site. Seminars on the subject to different audiences (industrial and academic) with varying expertise (signal processing, communications, circuit design) will be offered to disseminate the intermediate results and inquire about collaboration opportunities.

The PhD student will first work on simplified illustrative scenarios and numerical evaluations, and then move onto more comprehensive scenarios. Master and undergraduate theses will also be offered. These theses will focus on numerical evaluations and the measurement tasks in WP3. The schedule of WP3 tasks in Table 1 is chosen to be consistent with the timing of the announcement the thesis work within the academic calendar.

In order to fully evaluate the possible societal impact of our work, the services offered by the research utilization office, Innovation Office West will be used. We will collaborate with Ericsson in terms of implications of our results for machine-to-machine communications. Intellectual Property Rights (IPR) will be a particularly important issue in the light of this collaboration. The strategies we should adopt on IPR related issues will be determined with the help of Innovation Office West. For dissemination to non-technical audiences, we will implement the following actions: i) development of a web-page for the project with easily accessible synopses of the project ii) interview with the local newspapers, such as Göteborgs-Posten and NyTeknik, iii) participation in International Science Festival in Gothenburg.

Month / Activity	1-6	7-12	13-18	19-24	25-30	31-36	37-42	43-48
WP1	WP1.1	WP1.2	WP1.2					
WP2				WP2.1	WP2.1	WP2.2	WP2.2	WP2.2
WP3		WP3		WP3		WP3		WP3

TABLE I: Time Table for the Project.

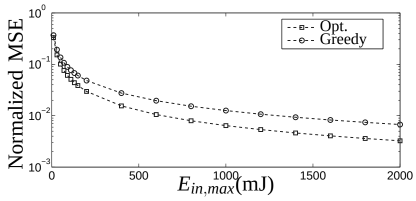


Fig. 3: Optimized versus greedy approach

IV. Significance

With the increasing number of mobile devices and wireless sensing applications, and the ever increasing demand on energy resources, efficient and smart usage of our resources in our sensing and communication systems is an urgent priority. In this respect, energy harvesting is a promising approach whose market share is expected to reach approximately 1.9 billion dollars by 2017 [3]. Demonstrations that illustrate the potential of such systems are also highly regarded by communities focusing on green technologies; see, for instance, the prizes Swedish start-up *ReVibe Energy* focusing on energy harvesting from vibrations have earned [6]. In addition to mobility and prolonged network life-times, EH capabilities also offer possibilities for “energy autonomous” sensing systems [1–3]. The project we propose here will contribute to the development of sensing systems with such EH features.

The timing of the project provides us an important opportunity. At the moment, the information-theoretic studies continue to provide us knowledge on the fundamental limits of EH communication networks. On the other hand, practical systems that make usage of simplistic EH ideas have started to emerge. It is important that the gap between these two realms are bridged and efficient sensing and communication strategies are developed and standardized into our systems.

This project is particularly timely from the upcoming 5G standard perspective. Systems with EH capabilities are expected to be parts of this standard [34]. Using EH capabilities is considered a promising candidate for powering machine-type communications, which is an important use case for 5G [35]. It is imperative that this standard is developed with the awareness of the limitations posed by EH capabilities for our sensing systems and the relevant solutions.

In particular, this project will provide novel and significant contributions for sensing systems with EH capabilities as follows: We will address the sensing and the relevant inverse problem aspects together with communication aspects. This will allow us to optimize our sensing and communication strategies more efficiently, for instance by exploiting the spatial correlation of the field that is measured. We will emphasize low-complexity communication solutions and multi-sensor scenarios. Without considering such aspects, it is not possible to fully understand the practical limitations posed on sensing operations by using EH devices. Through these studies, our project will reveal the basic limitations posed by utilizing unreliable energy resources in our sensing systems and provide guidelines for future sensing systems which cannot be provided by the current approaches.

The project will also make significant contributions for human resources development: The PhD student will not only have a solid background in the intersection of signal processing and communications, but will also have extensive knowledge in the rapidly growing field of EH communication systems. The undergraduate and Master theses offered within the project will not only expose the students to research methodology, but will also allow them to work close to the cutting edge EH technology with many possible inspiring applications, which can be instrumental for convincing them to pursue research or entrepreneurship-oriented careers.

V. Preliminary Results

My work on distributed estimation (without EH constraints) will serve as preliminary work for this project [16], [27], [36]. These works provide us sensing guidelines, i.e. guidelines about “how many measurements to make and with what accuracy” under the assumption there is always enough power to collect and send the information. This proposal can be considered as an extension of these results to the scenarios where the energy source is intermittent.

My work in [37] corresponds to the study of a limiting case for the intermittent energy scenarios in this project. In [37] we have considered minimum mean-square error (MMSE) estimation under Gaussian erasure channel. This setting can be interpreted as an EH scenario where sensors do not have any batteries and hence they send their data if energy can be harvested (i.e. no erasure occurs) or no energy can be harvested and data is dropped (i.e. erasure occurs). In that work, we have showed that it is possible to recover the unknown signal with a low MMSE from a small number of measurements provided that the signal family has low degrees of freedom. This observation has facilitated connections with compressive sensing [17]. We expect similar connections will be drawn in the proposed project which relates the reliability of the EH sources and the degrees of freedom of the signal family.

My recent work on energy harvesting focuses on linear precoding solutions for RF energy transfer [38], [39]. In these works, the key concern is to design transmission strategies for simultaneous information and energy transfer. Although the formulations in these works are different from this proposed project, the tools we have developed, in particular methods for finding rank-constrained solutions, will be utilized here for finding linear precoding strategies.

We provide a comparison of the performance of optimized linear precoding solutions (WP1-Task 5) with the greedy approach for mean-square error (MSE) minimization in Fig. 3. We adopt a model which is an extension of the offline, time slotted single-input single-output scenario in [8] to MIMO linear precoding case. In the greedy approach, no optimization over the transmission time frame is done, an energy packet is used as soon as it becomes available. The plots show the average error performance versus $E_{in,max}$ when the energy packet sizes are generated as i.i.d. uniformly in $[0, E_{in,max}]$ (mJs) [11]. It is observed that the optimized approach provides substantial performance improvements over the greedy approach. As $E_{in,max}$ increases, the performance gap between the two schemes does not diminish. This illustrates that when high performance is desired, optimization over the a time frame can be advantageous even in cases where the EH source has a very good peak performance. In the project, we will further extend these results to multi-sensor scenarios and the online optimization scheme.

VI. Independent Line of Research

The project proposed here utilizes my previous experience in sensing, information theory and signal processing (mostly Ph.D. work) and communications (mostly post-doctoral work) and combines them to address energy harvesting problems described above. Although the project benefits from both of these sets of expertise, it creates a unique line of research by considering energy harvesting systems and focusing on aspects that will be difficult to address if one were to focus on only one of these aspects.

This VR grant will offer me the opportunity to fully develop an independent line of research. With the financial stability the grant provides, it will be easier to look into fundamental and challenging research problems with high chances of substantial impact (such as online optimization with random energy arrival in a multi-sensor environment) in contrast being restricted to the problems that will have immediate output but limited impact (such as offline optimization with full information on energy arrival in a single sensor scenario).

In this regard, I will have an opportunity to exhibit a greater impact on the energy and sensing related societal challenges and establish myself in this field as a significant contributor. Here, the timeliness of the project in the light of the connections between the proposed project and scientific priorities set by Swedish Research Council and European Commission Framework Horizon 2020, in particular, energy efficiency, and smart home and smart cities applications will play an important role.

VII. Form of employment

Currently I am employed at Chalmers University of Technology as a post-doctoral researcher. Chalmers guarantees a fixed term research position through the duration of the VR project.

VIII. International and National Collaboration

In addition to my current collaboration with Tomas McKelvey and Mats Viberg, Signals and Systems Department at Chalmers, initial steps for collaboration with Mikael Coldrey and Giuseppe Durisi from the same department have also been taken. Collaboration with Ericsson Research has been initiated. I gave two talks on energy harvesting at Ericsson up to now. We are currently working on a schedule that will allow me to have more regular visits. Here we will focus on 5G use cases with machine-type communications. By considering sensing aspects together with communications, we will be developing insights that would be difficult to produce if one of the parties were working alone.

In WP1-WP3, I will collaborate with Deniz Gündüz, Dept. of Electrical and Electronic Engineering, Imperial College London, UK who is a leading researcher in the area of energy harvesting communication networks. We are currently working on a plan that will enable a series of research visits. I will also collaborate with Serdar Yüksel, Dept. of Mathematics and Statistics, Queen's University, Canada on WP2. His expertise on Markov sources and stochastic optimization will be particularly important. Our previous work in [37], which can be considered as a study of a limiting case of this proposed project, will serve as a good starting point.

References

[1] J. M. Gilbert and F. Balouchi, "Comparison of energy harvesting systems for wireless sensor networks," *International Journal of Automation and Computing*, vol. 5, pp. 334–347, Oct. 2008.

[2] R. Vullers, R. Schaijk, H. Visser, J. Penders, and C. Hoof, "Energy Harvesting for Autonomous Wireless Sensor Networks," *IEEE Solid-State Circuits Magazine*, vol. 2, no. 2, pp. 29–38, 2010.

[3] D. Gunduz, K. Stamatiou, N. Michelusi, and M. Zorzi, "Designing intelligent energy harvesting communication systems," *IEEE Communications Magazine*, vol. 52, no. 1, pp. 210–216, 2014.

[4] H. J. Visser and R. J. M. Vullers, "RF Energy Harvesting and Transport for Wireless Sensor Network Applications: Principles and Requirements," *Proceedings of the IEEE*, vol. 101, pp. 1410–1423, June 2013.

[5] M. Gorlatova, A. Wallwater, and G. Zussman, "Networking low-power energy harvesting devices: Measurements and algorithms," *IEEE Transactions on Mobile Computing*, vol. 12, no. 9, pp. 1853–1865, 2013.

[6] http://revibeenergy.com/press. Retrieved on 2015/03/01.

[7] "EnOcean technologies– energy harvesting –white paper." https://www.enocean.com, July 2011.

[8] O. Ozel, K. Tutuncuoglu, J. Yang, S. Ulukus, and A. Yener, “Transmission with energy harvesting nodes in fading wireless channels: Optimal policies,” *IEEE Journal on Selected Areas in Communications,*, vol. 29, pp. 1732–1743, Sep. 2011.
[9] J. Yang and S. Ulukus, “Optimal Packet Scheduling in an Energy Harvesting Communication System,” *IEEE Transactions on Communications*, vol. 60, pp. 220–230, Jan. 2012.
[10] B. Devillers and D. Gunduz, “A general framework for the optimization of energy harvesting communication systems with battery imperfections,” *Journal of Communications and Networks*, vol. 14, no. 2, pp. 130–139, 2012.
[11] K. Tutuncuoglu and A. Yener, “Optimum transmission policies for battery limited energy harvesting nodes,” *IEEE Transactions on Wireless Communications,*, vol. 11, pp. 1180–1189, March 2012.
[12] O. Ozel and S. Ulukus, “Achieving AWGN capacity under stochastic energy harvesting,” *IEEE Transactions on Information Theory*, vol. 58, pp. 6471–6483, Oct 2012.
[13] I. Bahceci and A. Khandani, “Linear estimation of correlated data in wireless sensor networks with optimum power allocation and analog modulation,” *IEEE Transactions on Communications*, vol. 56, pp. 1146–1156, July 2008.
[14] H. Zhang, J. Moura, and B. Krogh, “Dynamic field estimation using wireless sensor networks: Tradeoffs between estimation error and communication cost,” *IEEE Trans. Signal Process.*, vol. 57, pp. 2383–2395, June 2009.
[15] A. Dogandzi and K. Qiu, “Decentralized random-field estimation for sensor networks using quantized spatially correlated data and fusion-center feedback,” *IEEE Trans. Signal Process.*, vol. 56, pp. 6069–6085, Dec. 2008.
[16] A. Özçelikkale, H. M. Ozaktas, and E. Arıkan, “Signal recovery with cost constrained measurements,” *IEEE Trans. Signal Process.*, vol. 58, pp. 3607–3617, July 2010.
[17] D. Donoho, “Compressed sensing,” *IEEE Trans. Inf. Theory*, vol. 52, pp. 1289–1306, Apr. 2006.
[18] A. Limmanee, S. Dey, and A. Ahlen, “Distortion minimization via multiple sensors under energy harvesting constraints,” in *IEEE 14th Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, pp. 225–229, June 2013.
[19] M. Nourian, S. Dey, and A. Ahlen, “Distortion Minimization in Multi-Sensor Estimation With Energy Harvesting,” *IEEE Journal on Selected Areas in Communications*, vol. 33, pp. 524–539, Mar. 2015.
[20] A. Nayyar, T. Başar, D. Teneketzis, and V. Veeravalli, “Optimal strategies for communication and remote estimation with an energy harvesting sensor,” *IEEE Transactions on Automatic Control,*, vol. 58, pp. 2246–2260, Sept 2013.
[21] M. Nourian, A. Leong, and S. Dey, “Optimal energy allocation for Kalman filtering over packet dropping links with imperfect acknowledgments and energy harvesting constraints,” *IEEE Trans. on Automatic Control*, vol. 59, pp. 2128–2143, Aug 2014.
[22] P. Castiglione, O. Simeone, E. Erkip, and T. Zemen, “Energy Management Policies for Energy-Neutral Source-Channel Coding,” *IEEE Transactions on Communications*, vol. 60, pp. 2668–2678, Sept. 2012.
[23] C. Tapparello, O. Simeone, and M. Rossi, “Dynamic Compression-Transmission for Energy-Harvesting Multihop Networks With Correlated Sources,” *IEEE/ACM Transactions on Networking*, vol. 22, pp. 1729–1741, Dec. 2014.
[24] Y. Zhang, S. He, J. Chen, Y. Sun, and X. S. Shen, “Distributed Sampling Rate Control for Rechargeable Sensor Nodes with Limited Battery Capacity,” *IEEE Transactions on Wireless Communications*, vol. 12, pp. 3096–3106, June 2013.
[25] S. Cui, A. Goldsmith, and A. Bahai, “Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks,” *IEEE Journal on Selected Areas in Communications*, vol. 22, pp. 1089–1098, Aug 2004.
[26] V. Raghunathan, S. Ganeriwal, and M. Srivastava, “Emerging techniques for long lived wireless sensor networks,” *IEEE Communications Magazine*, vol. 44, no. 4, pp. 108–114, 2006.
[27] A. Özçelikkale and H. M. Ozaktas, “Beyond Nyquist sampling: a cost-based approach,” *J. Opt. Soc. Am. A*, vol. 30, pp. 645–655, Apr. 2013.
[28] A. E. Gamal and Y.-H. Kim, *Network Information Theory*. Cambridge University Press, 2012.
[29] Y. Dong, F. Farnia, and A. Ozgur, “Near optimal energy control and approximate capacity of energy harvesting communication,” *IEEE Journal onSelected Areas in Communications,*, vol. 33, pp. 540–557, March 2015.
[30] http://www.powercastco.com/.
[31] A. W. Marshall and I. Olkin, *Inequalities: Theory of Majorization and its Applications*. Academic Press, 1979.
[32] S. Yüksel and T. Başar, *Stochastic Networked Control Systems: Stabilization and Optimization under Information Constraints*. Springer, 2013.
[33] J. Nocedal and S. J. Wright, *Numerical Optimization*. Springer, 2006.
[34] J. Andrews, S. Buzzi, W. Choi, S. Hanly, A. Lozano, A. Soong, and J. Zhang, “What will 5G be?,” *IEEE Journal on Selected Areas in Communications*, vol. 32, pp. 1065–1082, June 2014.
[35] M.-J. Shih, Y.-C. Pang, G.-Y. Lin, H.-Y. Wei, and R. Vannithamby, “Performance evaluation for energy-harvesting machine-type communication in LTE-A system,” in *2014 IEEE Vehicular Technology Conference (VTC Spring),*, pp. 1–5, May 2014.
[36] A. Özçelikkale and H. M. Ozaktas, “Representation of optical fields using finite numbers of bits,” *Opt. Lett.*, vol. 37, pp. 2193–2195, June 2012.
[37] A. Özçelikkale, S. Yüksel, and H. Ozaktas, “Unitary precoding and basis dependency of MMSE performance for Gaussian erasure channels,” *IEEE Transactions on Information Theory*, vol. 60, pp. 7186–7203, Nov 2014.
[38] A. Özçelikkale and T. M. Duman, “Linear precoder design for simultaneous information and energy transfer over MIMO interference channels,” Submitted to IEEE Transactions on Wireless Communications.
[39] A. Özçelikkale, T. McKelvey, and M. Viberg, “Wireless information and power transfer in MIMO channels under Rician fading,” Accepted to 2015 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP).

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

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	Ayca Ozcelikkale	

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	2019	Total
1	Applicant	Ayca Ozcelikkale	20	160,000				160,000
2	Applicant	Ayca Ozcelikkale	66		545,000			545,000
3	Applicant	Ayca Ozcelikkale	75			640,000	660,000	1,300,000
4	Other personnel without doctoral degree	-	80	435,000	450,000	535,000	555,000	1,975,000
	Total			595,000	995,000	1,175,000	1,215,000	3,980,000

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	Total
1	Office	43,000	72,000	85,000	88,000	288,000
	Total	43,000	72,000	85,000	88,000	288,000

Running Costs

	Running Cost	Description	2016	2017	2018	2019	Total
1	Conference/Travel Costs		90,000	90,000	90,000	90,000	360,000
2	Computer	Computer for PhD Student	19,000				19,000
3	Laptop	Laptop for WP3	19,000				19,000
4	Consumables	Consumables for WP3	35,000	35,000	35,000	35,000	140,000
5	IT Costs		13,000	22,000	26,000	27,000	88,000
	Total		176,000	147,000	151,000	152,000	626,000

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	595,000	995,000	1,175,000	1,215,000	3,980,000		3,980,000
Running costs	176,000	147,000	151,000	152,000	626,000		626,000
Depreciation costs					0		0
Premises	43,000	72,000	85,000	88,000	288,000		288,000
Subtotal	814,000	1,214,000	1,411,000	1,455,000	4,894,000	0	4,894,000
Indirect costs	220,000	365,000	430,000	445,000	1,460,000		1,460,000
Total project cost	1,034,000	1,579,000	1,841,000	1,900,000	6,354,000	0	6,354,000

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

Project Leader

The engagement for the project leader is %58.95 (average over four years).

The project leader has an ongoing Marie Sklodowska-Curie Fellowship from European Union with the project title ``Green and Smart Communications with Energy Harvesting: A Signal Processing Approach". The period for this grant is March 2015- February 2017. That grant does not cover all the costs related to her employment. The VR grant together with Marie Sklodowska-Curie Fellowship will be used to cover her employment costs until February 2017.

For 2016, %20 engagement for the VR project is provided.

For January-February 2017, %20 engagement for the VR project is provided. For March-December 2017, %75 engagement for the VR project is provided. This corresponds to %65.83 engagement on average on 2017.

For 2017-2019, %75 engagement for the VR project is provided.

Doctoral Student

The engagement for the PhD student is %80. The remaining costs of the PhD student will be covered by teaching and department duties.

Conferences/Travel

The travel cost per person (for attending conferences, workshops, and holding research visits) is calculated as 45tkr per year. One travel across the continent and one travel within Europe is assumed with the corresponding costs, 30tkr and 15 tkr, respectively.

Computer

A personal computer for the PhD student.

Laptop

Laptop to use in the experiments in ``WP3: Measurements for Characterizing Energy Availability from Renewable Sources for Low-Power Devices".

Consumables

Consumables for ``WP3: Measurements for Characterizing Energy Availability from Renewable Sources for Low-Power Devices" and for the new/updated deployments over the years.

35tkr is calculated as follows:

(a) Energy Harvesting Development Kit for Wireless Sensors (Estimated price based on Powercast kits) (15tkr)
(b) Calibrated Photodetector (Estimated price based on 818-UV/DB) (7tkr)
(c) Optical Ambient light sensors (Estimated price based on TSL230RD-TRCT-ND): 100 sensor set (3tkr)
(d) Multifunction DAQ with USB (Estimated price based on U3-LV/U3-HV) (1tkr x 10 =10tkr)

Other items (IT costs, cost for premises) are calculated according to the Chalmers University of Technology guidelines.

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

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Ayça Özçelikkale

Chalmers University
Dept.of Signals and Systems
Gothenburg, Sweden
✉ *ayca.ozcelikkale@chalmers.se*

1. Higher Education Qualifications

2004 **B.Sc.**, *Middle East Technical University (METU), Dept. of Electrical Eng.*, Ankara, Turkey.

2004 **B.Sc.**, *Middle East Technical University, Dept. of Philosophy – Double Major*, Ankara, Turkey.

2006 **M.Sc.**, *Bilkent University, Dept. of Electrical Eng.*, Ankara, Turkey.
Supervisor: Haldun M. Ozaktas
Structural and Metrical Information in Linear Systems

2. Doctoral Degree

2012 **Ph.D.**, *Bilkent University, Dept. of Electrical Eng.*, Ankara, Turkey.
Supervisor: Haldun M. Ozaktas
Signal Representation and Recovery under Measurement Constraints

3. Post-Doctoral Positions

May 2014 – present **Post-Doctoral Researcher**, *Chalmers University, Dept. of Signals and Systems*, Gothenburg, Sweden.

- *Signal processing and communications for energy harvesting systems*

Sep. 2012 – Apr. 2014 **Post-Doctoral Researcher**, *Bilkent University, Dept. of Electrical Engineering*, Ankara, Turkey.

- *Multi-user communications*

4. Qualification required for appointments as a docent

- Completed the course "Supervision of Research: Principles and Practice". This is one of the teaching qualifications for being accepted as a docent at Chalmers.

5. Current Position

May 2014 – present **Post-Doctoral Researcher**, *Chalmers University, Dept. of Signals and Systems*, Gothenburg, Sweden.
%100 Research-based Appointment.

March 2015 – present **Marie Skłodowska-Curie Fellow**, *Chalmers University, Dept. of Signals and Systems*, Gothenburg, Sweden.
%100 Research-based Appointment.

6. Previous positions and periods of appointment

- Listed in Section 3. Otherwise not applicable.

7. Interruption in research

- Not Applicable.

8. Supervision

- Not Applicable.

9. Other merits of relevance to the application

Awards

2015 **European Union Marie Skłodowska-Curie Fellowship**.
Project title: "Green and Smart Communications with Energy Harvesting: A Signal Processing Approach".

2010 **Fellowship for Research Abroad during PhD Studies**.
Awarded by The Scientific and Technological Research Council of Turkey.

2007 **Best Student Paper Award, 2nd place**.
IEEE Signal Process. and Commun. App. Conf., Eskişehir, Turkey.

2005 -2011 **Graduate Scholarship**.
Awarded by The Scientific and Technological Research Council of Turkey, includes stipend for the duration of graduate studies.

2004 -2012 **Graduate Scholarship**.
Awarded by Bilkent University, includes tuition and stipend for the duration of graduate studies.

2001 **Bülent Kerim Altay Award**.
Awarded by Dept. of Electrical Engineering, METU for Fall Term GPA of 4.00/4.00.

2000 **Ranked 55th in the national university entrance exam**.

1993 **Ranked 3rd in the national high school entrance exam**.

Long Term Research Visits

Aug. 2010 – Jun. 2011 **Visiting Research Student**, *Queen's University, Department of Mathematics and Statistics*, Ontario, Canada.

Supervision of Master Theses

January 2015 – present **Kooros Moabber**, *Chalmers University, Dept. of Signals and Systems*, Gothenburg, Sweden.
Thesis Title: Energy Harvesting in Relay Channels – Simultaneous Information and Power Transfer

Publication list

Publications

1. Peer-reviewed original articles

* A. Özçelikkale, S. Yüksel, and H. M. Ozaktas, "Unitary Precoding and Basis Dependency of MMSE Performance for Gaussian Erasure Channels", *IEEE Trans. Information Theory* , vol. 60, no. 11, pp. 7186-7203, Nov. 2014.

A. Özçelikkale, and T. M. Duman, "Short Length Trellis-Based Codes for Gaussian Multiple-Access Channels", *IEEE Signal Process. Lett.*, vol. 21, no. 10, pp. 1177-1181, Oct. 2014.

* A. Özçelikkale and H. M. Ozaktas, "Beyond Nyquist sampling: a cost-based approach," *J. Opt. Soc. Am. A*, vol. 30, no. 4, pp. 645–655, Apr. 2013.

A. Özçelikkale and H. M. Ozaktas, "Optimal representation of non-stationary random fields with finite numbers of samples: A linear MMSE framework," *Digital Signal Process.*, vol. 23, no. 5, pp. 1602 – 1609, Sept. 2013.

A. Özçelikkale and H. M. Ozaktas, "Representation of optical fields using finite numbers of bits," *Opt. Lett.*, vol. 37, pp. 2193–2195, Jun. 2012.

* A. Özçelikkale, H. M. Ozaktas, and E. Arıkan, "Signal recovery with cost constrained measurements," *IEEE Trans. Signal Process.*, vol. 58, no. 7, pp. 3607–3617, Jul. 2010.

2. Peer-reviewed conference papers

* A. Özçelikkale, Tomas McKelvey, and Mats Viberg, "Wireless Information and Power Transfer in MIMO Channels under Rician fading", *Proc. 2015 IEEE International Conference on Acoustics, Speech and Signal Processing*, Accepted.

A. Özçelikkale, and T. M. Duman, "Lower Bounds on the Error Probability of Turbo Codes", *Proc. 2014 IEEE Int. Symp. Information Theory*, pp. 3170-3174, June 2014.

A. Özçelikkale, S. Yüksel, and H. M. Ozaktas, "Average error in recovery of sparse signals and discrete Fourier transform (In Turkish: Seyrek işaretlerin geri kazanımında ortalama hata ve ayrık Fourier dönüşümü," in *Proc. 2012 IEEE Signal Process. and Commun. App. Conf.*, Apr. 2012 **(Finalist for Best Student Paper Award)**.

A. Özçelikkale, G. B. Akar, and H. M. Ozaktas, "Super-resolution using multiple quantized images," in *Proc. 2010 IEEE Int. Conf. on Image Processing*, pp. 2029–2032.

* A. Özçelikkale, H. M. Ozaktas, and E. Arıkan, "Optimal measurement under cost constraints for estimation of propagating wave fields," *Proc. 2007 IEEE Int. Symp. Information Theory*, pp. 696–700.

A. Özçelikkale, H. M. Ozaktas, and E. Arıkan, "Measurement strategies for input estimation in linear systems (In Turkish: Doğrusal sistemlerde girdi kestirimi için ölçüm yöntemleri)," in *Proc. 2007 IEEE Signal Process. and Commun. App. Conf.*, **(Best Student Paper Award, 2nd place)**.

3. Monographs

A. Özçelikkale, "Structural and metrical information in linear systems," Master's thesis, Bilkent University, Ankara, Turkey, 2006.

A. Özçelikkale, "Signal Representation and Recovery under Measurement Constraints," Ph.D. thesis, Bilkent University, Ankara, Turkey, 2012.

CV

Name: Ayca Ozcelikkale	**Doctorial degree:** 2012-09-11
Birthdate: 19820116	**Academic title:** Doktor
Gender: Female	**Employer:** Chalmers tekniska högskola

Research education

Dissertation title (swe)
Signal Representation and Recovery under Measurement Constraints

Dissertation title (en)
Signal Representation and Recovery under Measurement Constraints

Organisation	Unit	Supervisor
Bilkent University, Turkey Not Sweden - Higher Education institutes	Department of Electrical and Electronics Engineering	Haldun Ozaktas

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
20205. Signalbehandling		2012-09-11

Publications

Name: Ayca Ozcelikkale	**Doctorial degree:** 2012-09-11
Birthdate: 19820116	**Academic title:** Doktor
Gender: Female	**Employer:** Chalmers tekniska högskola

Ozcelikkale, Ayca 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
- any additional professional activities or commercial ties have been reported to the administrating organisation, and that no conflicts have arisen that would conflict with good research practice
- 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.

Project out lines are not signed by the administrating organisation. The administrating organisation only sign the application if the project outline is accepted for step two.

Applications with an organisation as applicant is automatically signed when the application is registered.