Application

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2015-04708 Codreanu, Ionel Marian NT-14

Information about applicant

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Information about application

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Keywords: compressed sensing, wireless networking, mathematical optimization, machine to machine communications

Funds applied for

Year:	2016	2017	2018	2019
Amount:	1,741,450	1,769,788	1,798,692	1,828,174

Descriptive data

Project info

Project title (Swedish)*

”Compressed Sensing”-tekniker för trådlösa sensornätverk

Project title (English)*

Compressed Sensing Techniques for Wireless Sensor Networks

Abstract (English)*

Recently discovered compressed sensing theory reveals an entirely new perspective on the basic principles governing data acquisition, compression, and reconstruction and suggests radically new ways of handling massive amounts of data in wireless networks with substantial saving in terms of energy, bandwidth, and computational complexity. The main goal of this project is to understand the fundamental design principles and investigate the ultimate capabilities of compressed sensing techniques in wireless sensor networks.
What distinguish this work from prior related work is that it addresses large sensor networks that rely only on wireless interconnections (without the support of a preexisting infrastructure) and are subject to arbitrary temporal and spatial variability (caused, e.g., by channel fading, addition/removal of nodes, node mobility, etc.). We propose an optimization-based methodology which integrates compressed sensing and wireless data transport into a unified optimization framework which will serve as the mathematical basis for a systematic design and, ultimately, will reveal the performance limits.
This work will provide both mathematical characterizations of the optimal tradeoffs between different fundamental performance criteria (e.g., energy versus sensing accuracy) and practical algorithms and hierarchically structured network protocols able of handling large amount of data with lower energy and bandwidth consumption than in existing systems. In addition, the proposed research will provide a deep understanding of the fundamental design principles and it will contribute to the efforts of enabling the internet-of-things (IoT).
At the theoretical level, the ultimate goal is to develop the foundations for a general theory of compressive sensing in wireless sensor networks which includes all aspects mentioned above. This is indeed a very ambitious objective as it requires advanced mathematical skills to interconnect and apply knowledge from different disciplines, including Mathematical Optimization, Signal Processing, Information Theory, Control, and Statistics. However, such theory will have a breakthrough-making impact. In addition to the direct application on the wireless sensor networks, it will likely impact the science of network and data processing in other fields, including economics, transportation, biology, etc. Of course, developing a general theory which includes all aspects mentioned above requires long-term basic research. Along the way useful intermediary results with reduced generality (e.g., valid only for some particular network structures or under certain idealized assumptions) will be produced.
Publications in the most prestigious international scientific journals and conferences as well as doctoral theses and inventions will be produced as a concrete outcome of the project. Specifically, about 15 (fifteen) journal papers, 25 (twenty five) conference papers, and 1 (one) doctoral thesis are expected. In terms of the results dissemination, an ultimate goal is to publish a book based on the results. Considering the uniqueness and importance of the topics covered by this project, it would be widely accepted by the research community. An annual seminar to present research results will also be organized. In addition, special sessions in conferences and special issues in journals are planned to be organized with the collaborating partners

Popular scientific description (Swedish)*

Den nyligen framtagna teorin för Compressed Sensing (CS) erbjuder ett helt nytt perspektiv på de grundläggande principerna för insamling, komprimering och rekonstruktion av data. Syftet med detta projekt är att förstå grundläggande principer och analysera gränserna för hur CS kan prestera inom tillämpningen trådlösa sensornätverk. Målet är att integrera CS och trådlös överföring av data (dvs. effekt- och överföringskontroll, schemaläggning i noder och vägval) till ett enhetligt matematiskt optimeringsramverk som ska erbjuda den matematiska grunden för systematisk design, och slutligen ge möjlighet att ta fram teoretiska gränser för prestanda. Effektiva algoritmer och protokoll som kan hantera stora mängder data med reducerad åtgång av energi och bandbredd kommer härledas i projektet.

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 > 20204. Telekommunikation
	2. Teknik > 202. Elektroteknik och elektronik > 20203. Kommunikationssystem
	2. Teknik > 202. Elektroteknik och elektronik > 20202. Reglerteknik

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

Keyword 1*

compressed sensing

Keyword 2*

wireless networking

Keyword 3*

mathematical optimization

Keyword 4

machine to machine 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*

The research does not raise any ethical issues. It does not includes handling of personal data, animal experiments or experiments on humans.

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

Compressed Sensing Techniques for Wireless Sensor Networks

Marian Codreanu, Linköping University

1 Purpose and aims

Recently discovered *Compressed Sensing* (CS) theory [1–4] reveals an entirely new perspective on the basic principles governing data acquisition, compression, and reconstruction and suggests radically new ways of handling massive amounts of data in wireless networks with substantial saving in terms of energy, bandwidth, and computational complexity.

The **general goal** of this project is to understand the *fundamental design principles* and investigate the *ultimate capabilities* of *compressed sensing* in *wireless sensor networks*. Our emphasis is on large sensor networks that rely on wireless interconnections (without the support of a pre-existing infrastructure) and are subject to arbitrary temporal and spatial variability (caused, e.g., by channel fading, addition/removal of nodes, node mobility, etc.). The considered performance criteria are: **1**) energy efficiency or network lifetime (for battery powered nodes); **2**) sensing accuracy or sensing capacity [5] (for sensor networks deployed to monitor large-scale phenomena); **3**) robustness against nodes failure; **4**) scalability of the data gathering protocol.

The **basic hypothesis** of the research is that the information collected by different sensor nodes (see Figure 1) is correlated which implies that distributed compression schemes are needed [6–8]. The **working hypothesis** is based on the following two observations (explained in detail in Section 2): **1**) CS provides substantial savings in terms of clock rate, memory and computation at the sensor nodes; **2**) CS rely on a simple data gathering protocol since the sink needs to collect just a reduced number of linear combinations of the sensor readings. Therefore, we expect that the integration of compressed sensing and wireless networking will provide: **1**) increased energy efficiency, therefore, longer network lifetime; **2**) higher sensing accuracy and sensing capacity; **3**) increased robustness against nodes failure; **4**) better scalability of the data gathering protocol.

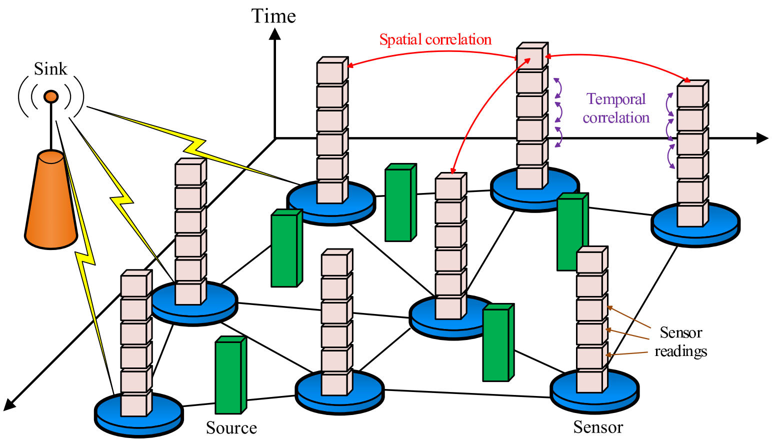

Figure 1: A generic wireless sensor network: the sensor readings are spatially and/or temporally correlated.

The **concrete goal** is to integrate compressed sensing and wireless data transport (i.e., power and rate control, node scheduling, routing) into a unified mathematical optimization framework which will provide the mathematical basis for a systematic design and, ultimately, will reveal the performance limits. In this framework, the considered performance criterion is reflected by an appropriate choice of the objective function (e.g., energy consumption) and the requirements imposed by the specific application (e.g., a minimum sensing resolution or a maximum response time) are modeled as constraints in the optimization program. Efficient design techniques and hierarchically structured network protocols will be derived by employing optimization decomposition techniques [9, 10] to break the original optimization problem into several (simpler) subproblems which are independently optimizing their variables. Each subproblem will correspond to a functional block, but, coordinated by a master program, they can still achieve global optimality.

We have already made progress and have results that show the utility of this method [11–16]. The main advantage of this approach is that it provides both useful insight for deriving simple enough (possibly suboptimal) solutions for real implementation and the yardstick to evaluate their distance from the optimal performance. Moreover, since there are multiple ways to decompose the original optimization problem, the design can be further improved by exploring the space of alternative decompositions and choosing the most suitable one, e.g., one that requires lower computational complexity or lower amount of nodes coordination. This approach will also reveal separation theorems by identifying the functional blocks which can be independently optimized (i.e., don't require mutual coordination).

The **ultimate goal** is to develop the foundations for a general theory of compressive sensing in wireless sensor networks which includes all aspects mentioned above. This is indeed a very ambitious objective as it requires advanced mathematical skills to interconnect and apply knowledge from different disciplines, including Mathematical Optimization, Signal Processing, Information Theory, Control, and Statistics. However, such theory will have a breakthrough-making impact. In addition to the direct application on the wireless sensor networks, it will likely impact the science of network and data processing in other fields, including economics, transportation, biology, etc. Of course, developing a general theory which includes all aspects mentioned above requires long-term basic research. Along the way useful intermediary results with reduced generality (e.g., valid only for some particular network structures or under certain idealized assumptions) will be produced.

2 Survey of the field

2.1 Compressed sensing in a nutshell

Compressed Sensing (CS) theory, emerged in 2006 from the seminal work of Donoho, Candés, Romberg, and Tao [1–4], provides an entirely new, sometimes paradoxical, perspective on the fundamental principles governing data acquisition, compression, and reconstruction. In a nutshell, CS predicts that compressible signals can be reconstructed from what was previously believed to be an incomplete set of measurements (or information). For example, by recognizing that the intrinsic information content of an analog signal is not dictated by its bandwidth, CS provides ways to sample a large class of signals at rates far bellow the Nyquist rate [17, 18] and then to reconstruct them asymptotically exact via efficient numerical methods [19–22].

While the CS theory does not contradict the Shannon-Nyquist sampling theorem, as the rule of sampling at the Nyquist rate is only a sufficient condition (but not a necessary one) for perfect signal recovery, the CS indeed changed radically the way we interpret and apply this criterion in practice. For example, *adaptive* sub-Nyquist rate sampling methods, based on *a priori knowledge of the spectral support* of the input signal, are known and frequently used by the signal processing community (see e.g., [23, 24]). The "CS paradox" comes from the fact that the sampling process is *nonadaptive* (i.e., independent of the input signal) but yet it is able to extract the information content of the input signal and condense it into a small amount of data. Thus, the striking fact is that CS provides an efficient way to *simultaneously perform signal acquisition and compression* without trying first to "comprehend the input signal" [25].

From a more general viewpoint, CS theory revealed that a high-dimensional but *compressible* signal can be reconstructed from an *incomplete* set of nonadaptive linear measurements. To make this statement precise and clarify the conditions under which the reconstruction is possible, let us consider a generic linear measurement model given by

$$\mathbf{y} = \mathbf{\Phi}\mathbf{x} \ , \tag{1}$$

where $\mathbf{x} = [x_1, \ldots, x_n]$ represents the signal of interest (that must be reconstructed), $\mathbf{y} = [y_1, \ldots, y_m]$ is the vector of available measurements, and $\mathbf{\Phi}$ is the $m \times n$ sensing (or measurement) matrix.

We are interested in the case of $m \ll n$, i.e., there are available far fewer measurements (or projections) than the dimension of $\mathbf{x}$. The CS theory states that if the signal of interest $\mathbf{x}$ have a concise representation in a certain basis (called representation basis), i.e., there is a basis $\boldsymbol{\Psi}$ and a *sparse* vector $\mathbf{s}$ such that $\mathbf{x} = \boldsymbol{\Psi}\mathbf{s}$, then the original signal $\mathbf{x}$ can be reconstructed as $\mathbf{x} = \boldsymbol{\Psi}\mathbf{s}^\star$, where $\mathbf{s}^\star$ is obtain by solving the l_1-norm optimization problem (i.e., liner program [26])

$$\mathbf{s}^\star = \underset{\tilde{\mathbf{s}}}{\operatorname{argmin}} \|\tilde{\mathbf{s}}\|_1 \quad \text{subject to} \quad \mathbf{y} = \boldsymbol{\Phi}\boldsymbol{\Psi}\tilde{\mathbf{s}} \ , \tag{2}$$

provided that

$$m \geq C \cdot \mu^2(\boldsymbol{\Phi}, \boldsymbol{\Psi}) \cdot S \cdot \log n \ , \tag{3}$$

where C is a constant, $\mu(\boldsymbol{\Phi}, \boldsymbol{\Psi})$ is the *coherence* [27] between $\boldsymbol{\Phi}$ and $\boldsymbol{\Psi}$, and S is the number of nonzero entries in $\mathbf{s}$. Thus, the number of measurements m needed to reconstruct $\mathbf{x}$,

1. depends *weakly* (i.e., logarithmically) on its dimension n;
2. increases proportionally with S (for fixed n); thus, roughly speaking, S represents the information content (or intrinsic dimension) of $\mathbf{x}$: as S decreases, $\mathbf{x}$ become more compressible;
3. increases with the coherence between the sensing matrix $\boldsymbol{\Phi}$ and the representation basis $\boldsymbol{\Psi}$ (for orthogonal matrices $\mu(\boldsymbol{\Phi}, \boldsymbol{\Psi}) \in [1, \sqrt{n}]$).

Therefore, by *properly designing* the sensing matrix $\boldsymbol{\Phi}$ to minimize the coherence with the representation basis $\boldsymbol{\Psi}$, the number of required measurements can be reduced to a few multiples of the intrinsic signal dimension (S) rather than to the dimension of the embedding space (i.e., n).

2.2 Compressed sensing based wireless sensor networks

In the context of *wireless sensor networks* (see Figure 1) the physical interpretation of the linear model (1) is as follows: x_i represents the reading of i'th sensor node, $y_1, \ldots, y_m$ represent m linear combinations of the sensor readings received at the fusion center (or sink), and $\boldsymbol{\Phi}$ depends on the specific data gathering protocol (i.e., routing, network coding or other in-network data aggregation, etc.). As discussed above, the sink needs to collect just m linear combinations of the sensor readings in order to reconstruct the entire map of the monitored field. This provides dramatic savings, especially in densely deployed sensor networks, machine-to-machine (M2M) communications and other internet-of-things (IOT) systems [28], where the number of nodes and the correlation between sensed data are large. However, to achieve this reduction the fusion center must know (or estimate and track) the representation basis $\boldsymbol{\Psi}$ and the data gathering protocol must be properly design to minimize $\mu(\boldsymbol{\Phi}, \boldsymbol{\Psi})$.

One of the earliest contributions that suggested the possibility of using CS techniques in wireless sensor networks is [29] (see also [30] for a more in-depth theoretical analysis). Specifically, the authors proposed an analog scheme where during a time-slot all sensor nodes transmit synchronously and in a phase-coherent manner their randomly-weighted measurements to a fusion center. Despite of several unpractical assumptions, such as perfect time and carrier phase synchronization across all the sensor nodes and the existence of non-fading equal-gain direct connections from each sensor to the fusion center, this pioneering work has the merit of pointing out the *universality* of these schemes.

A simple random access technique to communicate a random subset of the sensor readings along with theirs corresponding sensor's location tags to the fusion center was proposed in [31]. It eliminates the need of network-wide sensor synchronization but still the scheme relies on the existence of single-hop connections between each sensor node and the sink. Several heuristic routing algorithms for data gathering in multi-hop networks were proposed in [32, 33] and investigated via computer simulations, but no theoretical performance analysis was provided. The tradeoff between communication cost and delay in a sensor network with packet erasure was studied in [34]. Distributed coding of CS measurements using vector quantization were introduced in [35]. Wideband spectrum sensing methods based on sub-Nyquist sampling and are discussed in [36, 37].

The most widely used signal reconstruction algorithms are either based on convex optimization [19] or on greedy pursuit [21]. Both methods are computationally practical and lead to provably correct solutions under well-defined conditions [20]. Empirically tuned algorithms for CS applications are provided in [22]. Warm start methods for fast reconstruction of streaming signals are presented in [38]. A Bayesian formalism, where the decoder has a prior belief that the signal is sparse in a certain basis and the goal is to provide a posterior belief for the signal representation based on the newly received data was introduced in [39]. In this way the receiver can compute both the reconstructed signal and a measure of confidence in it. This creates a natural framework for adaptive compressed sensing algorithms [40, 41].

3 Project description

3.1 Project organization and implementation

The proposed research will take place at the Department of Science and Technology (ITN) of Linköping University (Norrköping Campus) under the supervision of the principal investigator (PI) Dr. Marian Codreanu. The PI is currently a part-time guest associate professor at ITN and he will devote at least 20% of his full time equivalent (FTE) to the proposed project for the entire four-years duration of the project (1 Jan. 2016 – 31 Dec. 2019). One doctoral student and one postdoctoral researcher will be hired and they will devote 80% of their FTE to this project. Thus the requested funding is intended to cover: 1) partially the salaries of the PI (20% FTE), doctoral student (80% FTE) and postdoctoral researcher (80% FTE); 2) travel and publications costs associated with the project activities; 3) the overheads charged by ITN-LiU.

An advisory team including Prof. Di Yuan from ITN-LiU and the international research partners Prof. Anthony Ephremides from University of Maryland and Prof. Behnaam Aazhang from Rice University will contribute with complementary scientific expertise to the proposed project. Prof. Di Yuan is the head of Mobile Telecommunications group at ITN-LiU, hosting the proposed work. He will contribute 15% of FTE to the project with his expertise on optimization and mathematical modeling and his salary will be covered by other ITN resources. The cooperation with the international partners is described in detail in Section 6.

In this project, a special attention is paid to determined and personalized supervision of doctoral students and postdoctoral researchers. The *research career* development is supported by active participation in scientific conferences and networking with the top researchers in the field. The PI will provide all the support necessary for the students' continuous development and progress as researchers. Publications in the most prestigious international scientific journals and conferences as well as a doctoral thesis and inventions will be produced as a concrete outcome of the project.

Risk management: The main risks are related to the unavoidable problems in implementing and demonstrating new technologies. This takes always time and effort and unexpected problems are naturally part of the process. However, the PI and the advisory team members have all long experience in handling and solving such problems. Therefore, we are confident that the risks are tolerable and well in control.

3.2 Research topics, time schedule and outputs

The proposed research is divided in the seven tasks described below. The PI will ensure the convergence of the different tasks and help the students to acquire quickly the necessary theoretical background. The practical advising of research will be made as joint effort of the PI and the advisory team. The whole personnel of ITN-LiU is naturally available to help in practical and scientific problems.

Task #1: Stochastic models for wireless sensor networks The connectivity in wireless sensor networks is often subject to constant changes. The goal of this task is to create an analytically tractable stochastic model of the wireless network, which should be accurate enough to capture the temporal and spatial variability caused by the channel fluctuations (fading), addition/removal of nodes, finite battery, node mobility, etc. Stochastic geometry provides a natural way to capture the spatial distribution of the nodes. By averaging over all potential geometrical patterns of the nodes the interference distribution and the link outage probabilities can be expressed in (or approximated by) closed form. Capturing network topologies changes caused by the finite lifetime of the sensor nodes is the most difficult task. The reason is that these changes are *random but non-ergodic and non-stationary.* This requires careful extensions of the standard modeling tools and very little is known in this area, so far.

- Time schedule: Jan. 2016 – Dec. 2017
- Outputs: 2–3 journal papers and 3–4 conference papers

Task #2: Modeling the energy consumption An accurate and yet analytically tractable model for the energy consumption in wireless sensor networks is essential for an accurate theoretical analysis as well as for deriving practical energy efficient network control mechanisms. The traditional models focus mainly on the energy of transmitted signals and they typically neglect other sources of energy loss, such us the power used by circuitry (e.g., the power amplifiers, baseband signal processing processors, frequency and A-D / D-A convertors, etc.) and the energy consumed by the network control mechanism. We aim to construct and use in our study more accurate energy consumption models, able to capture the underlying hardware characteristics as well as the computational complexity and associated overhead of the employed network control algorithms and protocols.

- Time schedule: Jan. 2016 – Jun. 2017
- Outputs: 1–2 journal papers and 2–3 conference papers

Task #3: Estimation and adaptive tracking of the representation basis A frequently used assumption in CS theory is that the representation basis (or, more generally, dictionary) is known at the reconstruction point and it remains fixed in time. However, in real world applications, the statistical characteristics of the signals of interest are often time-varying which imply that the representation basis that provides the sparsest (or sparse enough) representation for the signal of interest changes, as well [41]. As discussed in Section 2.1, the efficiency of CS rely precisely on the sparsity of this representation. Furthermore, in real applications the signals are not exactly sparse but only approximately sparse and the measured data are invariably affected by noise (physical noise in the measurement of finite precision, etc.). Therefore, in this task we focus on deriving computationally efficient *adaptive* CS algorithms able to estimate and then track the representation basis, e.g., by extracting the relevant statistical properties from the past collected data. A Bayesian formalism [39], where the decoder can compute a measure of confidence in the reconstructed signal enables also the control of the reconstruction error by adaptively changing the number of collected measurements. This leads to a different type of adaptive CS algorithms that will be investigated within this task.

- Time schedule: Jan. 2017 – Dec. 2018
- Outputs: 2–3 journal papers and 3–4 conference papers

Task #4: Energy versus sensing accuracy optimal tradeoff It is well known that if the *restricted isometry property* [25] holds, the performance of compressed sensing schemes degrades gracefully as the number of collected measurement decreases. Roughly speaking, instead of reconstructing the original signal, the decoder reconstructs a sparser approximation of it, and the sparsity of this approximation depends on the number of collected measurements. Thus, in the context of wireless sensor networks (WSN), this property enables connecting the energy consumption with the sensing accuracy. As these two are the main[1] performance criteria in WSN, this

[1] In certain applications, such as abnormal event detection, the error reconstruction is not a relevant criteria. In such cases we will use similar methodology to study energy versus response time optimal tradeoff.

task focuses on characterizing the optimal tradeoff curve (or Pareto boundary) between them by incorporating the energy consumption model developed in Task #2 into the holistic network optimization model described in Section 1. We are fully aware that solving the resulting optimization problem for the general case may pose formidable challenges (or may even be intractable). However, we are confident that finding at least close-to-optimal approximate solutions is both possible and insightful. These solutions will reveal the guiding design principles for practical schemes.

- Time schedule: Jan. 2018 – Dec. 2019
- Outputs: 2–3 journal papers and 3–4 conference papers

Task #5: Optimized data gathering protocols for multihop sensor networks As explained in Section 2.2, the *sensing matrix* is determined by the network topology, routing rules, and in-network data aggregation protocols, the *representation basis* depends on the characteristics of the monitored field and the *performance* of CS scheme depends strongly on the coherence between the two matrices. This task focuses on finding lighter data gathering protocols which still can provide a low coherence. This involve an interesting tradeoff between compression and communication: on one hand sparse measurements matrices are preferred since they involve lighter protocols[2], but, in the same time, as the sparsity increases the coherence with representation basis increases, too. We will investigate both random and deterministic routing rules as well as the possibility of using network coding techniques. This task complements nicely Task #3, which will provide the estimation and tracking techniques for the representation basis.

- Time schedule: Jan. 2016 – Dec. 2018
- Outputs: 3–4 journal papers and 4–5 conference papers

Task #6: Application-customized reconstruction algorithms This tasks focusses on deriving customized reconstruction algorithms which exploit efficiently the particularities of the specific application. They will be particularly useful in applications where the measurement matrix is random (e.g., when random routing or network coding is used in the data gathering protocol) and, therefore, it has to be factorized in each reconstruction step. In such cases it is still possible to identify certain deterministic patterns (e.g., sparse sub-blocks) which can be efficiently exploited to reduce the computational complexity. Naturally, the employed methods and the resulting improvement varies from application to application, but in certain cases the decrease in complexity can be dramatic, e.g., from cubic to linear [26]. There are also applications where the signal of interest (or different parts of it) has to be reconstructed at distinct fusion nodes (located physically apart from each other) based on partial measurements. This calls for reconstruction methods which admits distributed implementation and rely on a small amount of message passing.

- Time schedule: Jan. 2017 – Dec. 2019
- Outputs: 3–4 journal papers and 4–5 conference papers

Task #7: Performance limits of distributed compressed sensing At the implementation level, the CS schemes have clear advantages over the traditional methods where data are first collected and compressed using information about the correlation between them and then sent to the fusion center. In contrast, the CS approach allow executing the compression and data transmission jointly and *without any information about the correlation between data*. Thus, the CS approach reduces significantly the computation load at the network nodes as well as the communication overhead needed to learn the data correlation at each node. This task focuses on characterizing the performance limits of CS schemes and comparing them with the traditional methods based on lossless Slepian-Wolf [7] or lossy Wyner-Ziv [8] source coding.

- Time schedule: Jan. 2018 – Dec. 2019
- Outputs: 2–3 journal papers and 3–4 conference papers

[2] Since each measurement collected at the fusion center is a linear combination of only few sensor readings

4 Significance

Despite the stunningly rapid development of wireless networking technologies and their applications, the need for further development continues to increase, as they have become a cornerstone of modern society. While the explosive need for high-resolution multimedia content delivery calls for a more *efficient spectrum utilization*, the *proliferation of sensor technologies* has led to new applications (so-called machine-to-machine (M2M) communications) that require efficient and automated operation through wireless connectivity but without direct and pervasive human supervision. Some of these include smart home operation, environmental monitoring, health care, situational awareness, security guarantees, and a multitude of specialized processes like modern manufacturing, transportation, robotics, and power grid control.

To support these applications and a variety of new possibilities it is necessary to develop new architectures and access methods that will resemble more those of infrastructure-less, ad hoc wireless networks, rather than those of the traditional wireless networks (e.g., cellular, WiFi, etc.) appended to the classical Internet. The messages that are created by machines and devices are typically based on measurements and often are the result of considerable processing of inputs from other devices. Usually, there are high levels of correlation amongst these messages. Thus there is a need to glean out the essential new information from the data that are accumulated as a result of the measurements and the inputs.

However, the existing traditional methods perform this operation very inefficiently. For more than 50 years, virtually all data acquisition schemes followed the same basic structure: the input signal is first acquired at the desired resolution, and then compressed using (computationally intensive) signal processing techniques that remove the redundancy. Thus, a large amount of raw data is collected during the acquisition stage just to be thrown away at the compression stage. This leads to a reduced *energy efficiency*, shorter *network lifetine*, and poor *scalability*. In sharp contrast, the emerging CS theory suggests computationally lighter methods which collect only the minimum amount of data (i.e., already compressed) needed to reconstruct the input signal at the desired resolution. However, the *performance limits* and the *fundamental tradeoffs* of these schemes are currently unknown and their theoretical characterization is a major goal of this project. In addition, the proposed research will also provide a deep understanding of the fundamental *design principles* as well as *concrete algorithms* and network protocols for real implementation and it will contribute to the efforts of enabling the internet-of-things (IoT).

In this project, we are particularly focusing on wireless sensor networks applications where the CS techniques have the potential to truly revolutionize their design. However, as the CS theory affects the fundamental principles which govern essentially all the modern information processing systems, the impact of the proposed research will extend far beyond sensor networks. This research involves a combination of state-of-the-art knowledge from correlated scientific fields and will generate added value by providing new tools and methodologies which will likely impact the science of network and data processing in other fields, including economics, transportation, biology, etc. As the field of CS is very young, the potential of generating both *theoretical breakthroughs* as well as valuable *intellectual property* rights is high. The following **concrete results** are expected:

- practical algorithms and hierarchically structured network protocols able of handling large amounts of data with lower energy and bandwidth consumption than in the existing systems
- practical signal reconstruction algorithms (software) at the fusion center
- energy vs. sensing accuracy optimal tradeoff curves (mathematical characterization and software solutions)
- quantifiable predictions on the impact of temporal and spatial variability on different performance criteria (e.g., energy consumption, sensing accuracy) of wireless sensor nodes
- mathematical characterization of the performance limits of distributed compressed sensing techniques

Publications in the most prestigious international scientific journals and conferences as well as doctoral theses and inventions will be produced as a concrete outcome of the project. Specifically, about 15 (fifteen) journal papers, 25 (twenty five) conference papers, and 1 (one) doctoral thesis are expected. In terms of the results dissemination, an ultimate goal is to publish a book based on the results. Considering the uniqueness and importance of the topics covered by this project, it would be widely accepted by the research community. An annual seminar to present research results will also be organized. In addition, special sessions in conferences and special issues in journals are planned to be organized with the collaborating partners.

5 Preliminary results

We made pre-studies and have preliminary results in several directions of the proposed research.

In [42] we introduced a novel CS-based data gathering method for correlated data field monitoring in multi-hop wireless sensor networks (WSN). Instead of conveying original sensor readings, the sensors deliver CS-aggregated measurements to the sink, leading to a reduced number of incurred transmissions in the WSN. The sink can reconstruct accurately the data via CS decoding based on a Kronecker representation basis [43] which exploits efficiently the joint spatio-temporal correlation in the multi-dimensional sensor signal structure. The numerical experiments indicated that the proposed method have a great potential to increase the energy efficiency of data gathering multi-hop WSNs.

In [11, 44] we investigated the problem of *joint* design of compressed acquisition and progressive reconstruction of spatially and temporally correlated sensor data data streams in WSN. We proposed a sequential CS method with sliding window processing, where at each time slot, the sink acquires CS measurements from a subset of sensors, and reconstructs a portion of sensor data streams – including the current readings – by exploiting the joint data dependencies via a Kronecker sparsifying basis. To further reduce the necessary sensor communications, we derived a recursive CS recovery method where, via a l_2-regularization in conjunction to reweighed l_1-minimization, the estimates from the preceding windows are causally exploited in the signal recovery. The numerical experiments illustrated the benefits of utilizing the joint signal dependencies and the prior information in the CS recovery: by adjusting the window size, our proposed method achieved higher reconstruction accuracy with a smaller number of required transmissions, and with lower decoding delay and complexity as compared to the state of the art CS methods.

Ia a different line of work [45, 46] we derived a Bayesian learning method for reconstructing a streaming signal from compressive measurements. The proposed method provides the full posterior distribution of the sparse coefficients rather than computing only point estimates as in the case of traditional l_1-minimization based reconstruction algorithms. Numerical experiments show that the prosed method achieves higher reconstruction accuracy than the state of the art l_1-homotopy based signal recovery algorithms [38].

6 International collaboration

The key **international research partners** with whom we already *agreed* a schedule for the research visits are:

- **Dr. Anthony Epremides** (Life Fellow IEEE), Prof. University of Maryland, USA, is a world leader and pioneer in bridging information theory and ad hoc networks.
- **Dr. Behnaam Aazhang** (Fellow IEEE), Prof. Rice University, USA, is a world renowned pioneer for helping to create the field of cooperative communications.

We agreed to organize yearly researcher exchanges (of one month duration) with each partner for the whole duration of the project. The planned visits will help combining our team expertise in optimization and signal processing with the partners' expertise on information theory, wireless networking, and cooperative communications, and thus the joint work will lead to cross-fertilization of these field. Furthermore, the Digital Signal Processing (DSP) group at Rice University is one of the *world leading group in Compressed Sensing* research [http://dsp.rice.edu/research/compressive-sensing]. In addition, at the University of Maryland there is a specialized lab for the design of prototype energy efficient wireless nodes. Thus, the cooperation with both partner institutions will be instrumental in achieving the goals of the proposed project.

There is also a *history of cooperation* between the applicant and the research partners. Since 2011, the applicant is co-advising a Ph.D. student jointly with Prof. B. Aazhang. The cooperation with Prof. A. Ephremides started in 2008 when the undersigned visited University of Maryland for two month. Cooperation is ongoing and consists of yearly research visits, conducting joint research, co-authorizing publications as well as organizing joint workshops. The outcome of this cooperation was published in one monograph, nine journal papers and a number of conference papers. Thus, the proposed project will help on maintaining and enhancing our cooperation.

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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	Ionel Marian Codreanu	20
2	Other personnel without doctoral degree	Doctoral student (newly-recruited)	80
3	Other personnel with doctoral degree	Posdoctoral researcher (newly-recruited)	80

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	2019	Total
1	Applicant	Marian Codreanu	20	163,680	166,954	170,293	173,699	674,626
2	Other personnel without doctoral degree	Doctoral student (newly-recruited)	80	386,880	394,618	402,510	410,560	1,594,568
3	Other personnel with doctoral degree	Postdoctoral researcher (newly-recruited)	80	476,160	485,683	495,397	505,305	1,962,545
	Total			1,026,720	1,047,255	1,068,200	1,089,564	4,231,739

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	Rent for offices	115,200	115,200	115,200	115,200	460,800
	Total	115,200	115,200	115,200	115,200	460,800

Running Costs

	Running Cost	Description	2016	2017	2018	2019	Total
1	Travel costs	attending conferences, research visits	100,000	100,000	100,000	100,000	400,000
2	Publication costs	publication fees	20,000	20,000	20,000	20,000	80,000
	Total		120,000	120,000	120,000	120,000	480,000

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	1,026,720	1,047,255	1,068,200	1,089,564	4,231,739		4,231,739
Running costs	120,000	120,000	120,000	120,000	480,000		480,000
Depreciation costs					0		0
Premises	115,200	115,200	115,200	115,200	460,800		460,800
Subtotal	1,261,920	1,282,455	1,303,400	1,324,764	5,172,539	0	5,172,539
Indirect costs	479,530	487,333	495,292	503,410	1,965,565		1,965,565
Total project cost	1,741,450	1,769,788	1,798,692	1,828,174	7,138,104	0	7,138,104

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

The proposed research will take place at the Department of Science and Technology (ITN) of Linköping University (LiU), Norrköping Campus, under the supervision of the principal investigator (PI) Dr. Marian Codreanu. The requested budget is targeted to cover:

1. salary costs for three ITN members, as detailed below, at different percentages of Full Time Equivalent (FTE) involvement;
2. the travel and publication costs associated with the project activities; and
3. the overheads charged by ITN-LiU.

1) **Salary costs**

The salary costs are intended to cover:

1. Dr. Marian Codreanu (PI) presently holds a part time guest associated professor position at the Mobile Telecommunications (MT) group of ITN-LiU led by Prof. Di Yuan. The PI will devote 20% of his FTE to the project. The requested budget is 20% of his FTE.
2. Newly-hired doctoral student. A doctoral student will be recruited and she/he will devote 80% of their FTE to the project, handling the day-to-day research activities from proof-of-concept to implementation, development and testing. The requested budget is 80% of her/his FTE, since the rest 20% will be covered by ITN teaching budget.
3. Newly-hired postdoctoral resercher. A postdoctoral researcher with strong background in mathematical modelling and optimization will be recruited and she/he will devote 80% of her/his FTE to the project. The requested budget is 80% of her/his FTE, since the rest 20% will be covered by ITN teaching budget.

For each of the salaries, the requested budget includes social contributions of 55% of the salary. A 2% annual increase is also assumed. The applicant holds guest associate professor contract which is expected to be renewed accordingly upon the successful funding of the current proposal. LiU is an equal-opportunities employer and the new PhD student and postdoctoral positions will be advertised in this spirit.

2) **Travel and publication costs**

Publications in the most prestigious international scientific journals will be produced to disseminate the project outcomes. The travel costs are meant to cover participation in scientific conferences to present papers based on the project results as well as to enable the international collaboration and research visits. To reduce the travel costs, the research visits will be combined with conference trips whenever this is possible.

3) **Overheads**

The ITN Department of LiU, where this project is hosted, applies 38% overhead to all cost categories. Personnel costs are topped with a further 64000SEK/FTE for local facilities remuneration. Thus the total yearly rent for the offices for the PI, doctoral student and postdoctoral researcher is: 64000*(20%+80%+80%)=115200 SEK.

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

CURRICULUM VITAE

Marian Codreanu

March 31, 2015

Personal data

- Full name : Ionel Marian Codreanu
- Date of birth: 3 May 1974
- Civic status: married, two children, Romanian citizen

1. Higher education qualifications

- 1997, **BSc**. in Applied Electronics, University Politehnica of Bucharest (UPB), Romania
- 1998, **MSc**. in Images, Forms and Artificial Intelligence, UPB, Romania

2. Doctoral degree

- 2007, **PhD**. in Telecommunications Engineering, Univ. of Oulu, Finland; adviser: Prof. Matti Latva-aho
  - thesis: Multidimensional adaptive radio links for broadband communications (**with honors**)
  - awarded as the **best doctoral thesis within the area of all technical sciences in Finland, 2007**

3. Postdoctoral positions

- **Jan. 2010 – Dec. 2012: Senior research fellow**, Centre for Wireless Communications, Univ. of Oulu
- **Sep. 2008 – Nov. 2008: Research visitor**, Univ. of Maryland, USA; host: Prof. Anthony Ephremides
- **Jan. 2008 – Dec. 2009: Postdoctoral fellow**, Centre for Wireless Communications, Univ. of Oulu

4. Qualification required for appointments as a docent

- **Jan. 2013**: **Docent** in Optimization and Control Techniques for Wireless Networks, Univ. of Oulu

5. Current positions

- **Mar. 2015 – Dec. 2015: Guest Associate Professor** (20%), Linköping University, Sweden
- **Sep. 2013 – Aug. 2018: Academy Research Fellow**, University of Oulu, Finland
  - a highly competitive position funded by the Academy of Finland, with a successes rate of about 10%
- **Jan. 2013 – now: Adjunct Professor**, Department of Communications Engineering, University of Oulu

6. Previous positions and periods of appointment

- **Aug. 2002 – Nov. 2007: Research scientist**, Centre for Wireless Communications, University of Oulu
- **Sep. 1998 – Jul. 2002 : Teaching assistant**, University Politehnica of Bucharest, Romania

7. Interruption in research

- not applicable

8. Supervision

- **Main supervisor** of 1 PhD. student: Uditha Wijewardhana (started 2012, expected graduation 2016)
- **Co-supervisor** of 4 PhD. students: Chathuranga Weeraddana (PhD. Dec. 2011), Satya Yoshi (2010 – now), Kalle Lähetkangas (2011 – now), Markus Leinonen (2011 – now)
- **International**: mentor for 2 PhD. student visitors from University of Maryland: Jeongho Jeon (PhD. 2013), Maice Costa (expected graduation 2015)

9. Other merits of relevance to the application

9.1 Funding

- **Academy of Finland**: ComingNets, Academy Research Fellow position, Sep. 2013 – Aug. 2018, **€ 425.005**, principal investigator;
- **Academy of Finland**: Supplementary funding for the research group associated with the Academy Research Fellow position, Sep. 2013 – Aug. 2016, **€ 209.818**, principal investigator;
- **Academy of Finland**: Energy efficient cognitive networking, Jan. 2012 – Dec. 2013, **€ 199.219**, principal investigator;
- **Academy of Finland**: Optimal cross-layer control for wireless networks, Postdoctoral Researcher's project, Jan. 2010 – Dec. 2012, **€ 273.000**, principal investigator;
- **Infotech Oulu**: funding for organizing the intensive course "*Stochastic Modeling of Communication Systems*" lectured by Prof. Evsey Morozov from the Russian Academy of Sciences, Sept. 2014, **€ 5.500**;

- **Infotech Oulu**: funding for organizing the intensive course "*Elements of Multi-User Information Theory*" lectured by Prof. Gerhard Kramer from Technische Universität München, Germany, Aug. 2012, **€ 5.500**;
- **Infotech Oulu Graduate School**: two years scholarship, 2005–2006, **€ 40.000**;
- **Nokia Foundation**: personal grant for doctoral studies, 2006, **€ 5.000**;
- **HPY Research Foundation**: personal grant for doctoral studies, 2006, **€ 4.000**;

9.2 Awards

- **Academy Research Fellow** position awarded by the Academy of Finland in 2013.
- **Best doctoral thesis within the area of all technical sciences in Finland in 2007**, awarded by the Finnish Association of Graduate Engineers (TEK) and the Engineering Society in Finland (TFiF).
- Co-author of the **second best paper**, Asilomar Conference on Signals, Systems and Circuits 2010.
- **First prize** at the Student's Scientific Communication Session, E12, 1998 awarded by IEEE Romanian section.

9.3 Publications summary (full list available at: `www.cwc.oulu.fi/~codreanu/publications.pdf`)

- **22** published peer-reviewed articles; **2** under review/revision
- **69** peer-reviewed conference papers (mostly IEEE)
- **1** monograph (in Foundations and Trends in Networking, Now Publishers)
- total number of citations: **800**; h-index: **15**; citations of the two most cited papers: **118, 102** (by Google Scholar statistics)

9.4 Professional service (selected)

- **Vice Chair of the IEEE Finland Section Communications and Information Theory** Joint Societies Chapter, 2011 – now
- University of Oulu representative in the Finnish Publication Forum (the Finnish body that maintains and develops the classification of scientific publication channels according to their quality), 2014 – now
- Chair of the UniOG's doctoral training follow-up group for one doctoral student and member of the follow-up groups of several others
- TPC co-chair of the 2'nd, 4'th & 5'th Nordic Workshop on System & Network Optimization for Wireless (SNOW) in 2011, 2013 & 2014
- TPC member of about 3 IEEE conferences each year (since 2008)
- Referee for funding agencies: Qatar National Research Fund (2013, 2014, 2015) and Romanian National Research Council and National Development and Innovation Council (2012)
- Co-founder and TPC co-chair of the First Nordic Workshop on on System & Network Optimization for Wireless, 2010
- Organizer of the postgraduate course *Stochastic Modeling of Communication Systems* lectured by Prof. Evsey Morozov from the Russian Academy of Sciences, Sept. 2014
- Organizer of the postgraduate course *Elements of Multi-User Information Theory* thought by Prof. Gerhard Kramer from Technische Universität München (TUM), in 2012
- Organizer of the postgraduate course *Review of Fundamentals of Wireless Ad Hoc Networking* thought by Prof. Anthony Ephremides from University of Maryland, 2009

9.5 International collaborators (selected)

- **Prof. Anthony Ephremides** (IEEE Life Fellow) from University of Maryland, USA
- **Prof. Behnaam Aazhang** (IEEE Fellow) from Rice University, USA
- **Prof. Gerhard Kramer** (IEEE Fellow) from Technische Universität München, Germany
- **Prof. Alhussein Abouzeid** from Rensselaer Polytechnic Institute

9.6 Teaching (selected)

- **2010/2011, 2012, 2014**: lecturer and examiner for **Convex Optimization with Applications in Wireless Communications and Networks** (10 ECTS credits)
- 2008/2009: co-lecturer for **two newly introduced** courses: **Convex Optimization** (10 ECTS credits) and **Advanced Convex Optimization** (5 ECTS credits)

Publication list

Publications

Marian Codreanu

March 31, 2015

Note: The number of citations are given according to **Google Scholar** database.

A. Five most cited publications

1. **M. Codreanu**, A. Tölli, M. Juntti, and M. Latva-aho, "Joint design of Tx-Rx beamformers in MIMO downlink channel," *IEEE Transactions on Signal Processing*, vol. 55, no. 9, pp. 4639–4655, Sept. 2007. [Number of citations: **118**]
2. A. Tölli, **M. Codreanu**, and M. Juntti, "Cooperative MIMO-OFDM cellular system with soft handover between distributed base station antennas," *IEEE Transactions on Wireless Communications*, vol. 7, no. 4, pp. 1428–1440, Apr. 2008. [Number of citations: **102**]
3. A. Tölli, **M. Codreanu**, and M. Juntti, "Linear multiuser MIMO transceiver design with quality of service constraints in cooperative networks," *IEEE Transactions on Signal Processing*, vol. 56, no. 7, pp. 3049–3055, July 2008. [Number of citations: **42**]
4. P. C. Weeraddana, **M. Codreanu**, M. Latva-aho, and A. Ephremides, "Weighted sum-rate maximization for a set of interfering links via branch and bound," *IEEE Transactions on Signal Processing*, vol. 59, no. 8, pp. 3977–3996, Aug. 2011. [Number of citations: **30**]
5. P. C. Weeraddana, **M. Codreanu**, M. Latva-aho, and A. Ephremides, "Resource allocation for cross-layer utility maximization in wireless networks," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 6, pp. 2790–2809, Jul. 2011. [Number of citations: **28**]

B. List of publications (past 8 years, 2007 – 2015)

Note: The five publications most relevant to the project are the **peer-reviewed original articles 15, 20** and the **peer-reviewed conference papers 59, 62, 65**, indicated by an asterisk symbol (*) in the list below.

B1. Peer-reviewed original articles (2007 – 2015, in chronological order)

1. **M. Codreanu**, M. Juntti, and M. Latva-aho, "Low complexity iterative algorithm for finding the MIMO-OFDM broadcast channel sum capacity," *IEEE Transactions on Communications*, vol. 55, no. 1, pp. 48–53, Jan. 2007. [Number of citations: **24**]
2. A. Tölli, **M. Codreanu**, and M. Juntti, "Compensation of non-reciprocal interference in adaptive MIMO-OFDM cellular systems," *IEEE Transactions on Wireless Communications*, vol. 6, no. 2, pp. 545–555, Feb. 2007. [Number of citations: **15**]

3. **M. Codreanu**, A. Tölli, M. Juntti, and M. Latva-aho, “Joint design of Tx-Rx beamformers in MIMO downlink channel,” *IEEE Transactions on Signal Processing*, vol. 55, no. 9, pp. 4639–4655, Sept. 2007. [Number of citations: **118**]
4. **M. Codreanu**, M. Juntti, and M. Latva-aho, “On the dual decomposition based sum capacity maximization for vector broadcast channels,” *IEEE Transactions on Vehicular Technology*, vol. 56, no. 7, pp. 3577–3581, Nov. 2007. [Number of citations: **9**]
5. A. Tölli, **M. Codreanu**, and M. Juntti, “Cooperative MIMO-OFDM cellular system with soft handover between distributed base station antennas,” *IEEE Transactions on Wireless Communications*, vol. 7, no. 4, pp. 1428–1440, Apr. 2008. [Number of citations: **102**]
6. A. Tölli, **M. Codreanu**, and M. Juntti, “Linear multiuser MIMO transceiver design with quality of service constraints in cooperative networks,” *IEEE Transactions on Signal Processing*, vol. 56, no. 7, pp. 3049–3055, July 2008. [Number of citations: **42**]
7. P. C. Weeraddana, **M. Codreanu**, W. Li, and M. Latva-aho, “Primal decomposition-based method for weighted sum-rate maximization in downlink OFDMA systems,” *EURASIP Journal on Wireless Communications and Networking*, vol. 2010, Article ID 324780, 9 pages, 2010. [Number of citations: **4**]
8. P. C. Weeraddana, **M. Codreanu**, M. Latva-aho, and A. Ephremides, “On the effect of self-interference cancelation in multihop wireless networks,” *EURASIP Journal on Wireless Communications and Networking*, vol. 2010, Article ID 513952, 10 pages, 2010. [Number of citations: **13**]
9. Z. Khan, J. Lehtomäki, **M. Codreanu**, M. Latva-aho, and L. A. DaSilva, “Throughput-efficient dynamic coalition formation in distributed cognitive radio networks,” *EURASIP Journal on Wireless Communications and Networking*, vol. 2010, Article ID 653913, 13 pages, 2010. [Number of citations: **9**]
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22. S. Joshi, U. Wijewardhana, **M. Codreanu**, and M. Latva-aho, "Maximization of worst-case weighted sum-rate for MISO downlink systems with imperfect channel knowledge," *IEEE Transactions on Communications*, submitted Oct. 2014, revised Feb. 2015.
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B2. Peer-reviewed conference papers (2007 – 2015, in chronological order)

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B3. Monographs

68. P. C. Weeraddana, **M. Codreanu**, M. Latva-aho, A. Ephremides, and C. Fischione, *A review of weighted sum-rate maximization in wireless networks*, Foundations and Trends in Networking, Now Publishers, 2012.

B4. Patents

69. **M. Codreanu**, A. Tölli, M. Juntti, and M. Latva-aho, *Communication method and system*, US Patent 8208963, Jun.26 2012.
70. **M. Codreanu**, A. Tölli, M. Juntti, and M. Latva-aho, *Data Transmission Parameter Optimization in MIMO Communications System*, US Patent 7627347, Dec.1 2009.
71. **M. Codreanu**, D. Tujkovic, and M. Latva-aho, *Data Loading Method, Transmitter, and Base Station*, US Patent 7356017, Apr.8 2008.

B5. Invited talks

72. **M. Codreanu**, "On the stability region of cognitive radio systems with imperfect sensing," Technical University of Munich (host: Prof. Gerhard Kramer), Munich, Germany, Dec. 12, 2013.
73. **M. Codreanu**, "Weighted sum-rate maximization for a set of interfering links – global optimum via branch and bound," Chalmers University of Technology, Gothenburg, Sweden, Oct. 29, 2012.
74. **M. Codreanu**, "Challenges in wireless systems and networks," Luleå University of Technology, Sweden, Apr. 5, 2012.
75. **M. Codreanu**, "Weighted sum-rate maximization for wireless networks," Luleå University of Technology, Sweden, Apr. 5, 2012.
76. **M. Codreanu**, "Global and distributed optimization methods for radio resource management in wireless communication networks," Renesas Mobile, Oulu, Finland, Nov. 11, 2011.
77. **M. Codreanu**, "Weighted sum-rate maximization for a set of interfering links: global optimum via branch and bound," Linköping University, Sweden, Oct. 4 2011.
78. **M. Codreanu**, "Challenges for the next decade in wireless communication systems and networks," Linköping University, Sweden, Oct. 4 2011.
79. **M. Codreanu**, "Energy efficiency of mobile broadband access networks," KTH Royal Institute of Technology, Stockholm, Sweden, Jun. 8 2011.
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81. **M. Codreanu**, "On the advantages of using multiuser receivers in wireless ad-hoc networks," in *The First Nordic Workshop on Cross-Layer Optimization in Wireless Networks*, Levi, Finland, Apr.7–9 2010.

CV

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Dissertation title (swe)

Dissertation title (en)

Multidimensional adaptive radio links for broadband communications

Organisation	Unit	Supervisor
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Subject doctors degree	**ISSN/ISBN-number**	**Date doctoral exam**
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Publications

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Codreanu, Ionel Marian has not added any publications to the application.

Register

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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.

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- the institution approves the cost-estimate in the application
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