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Descriptive data

Project info

Project title (Swedish)*

Distribuerad lagring baserad på glesa grafkoder

Project title (English)*

Rethinking Distributed Storage Based on Sparse-Graph Codes

Abstract (English)*

The design of efficient and reliable storage and delivery systems to cope with the unprecedented deluge of data of modern societies is one of the fundamental challenges of our generation and has given rise to the emerging research area of distributed storage (DS). In wired DS, such as data centers or peer-to-peer networks, data is stored in a distributed fashion across multiple inexpensive storage nodes that, together, provide the desired reliability. In wireless DS, data is stored closer to the end user, for example across several mobile devices, to avoid the wireless bandwidth bottleneck for data-hungry applications, such as video streaming. In both wired and wireless DS, the required resilience to node failures, which are the norm rather than the exception, is achieved by means of erasure correcting coding across storage nodes.

State-of-the-art wired DS systems are based on algebraic block codes, which provide reliability at the expense of storage overhead. However, the extraordinary increase of the digital data generated, fueled by applications such as social and media networks and cloud computing, desperately requires new ways to improve storage efficiency and reliability. On the other hand, the ever-increasing demand for higher quality content to wireless devices threatens to completely congest the cellular network. Research on wireless DS is at an even earlier stage and practical coding schemes are yet to be proposed. Thus, there is an array of opportunities for frontier research in the emerging research area of DS.

The purpose of this project is the design of novel erasure correcting coding schemes for next-generation DS systems. Our approach is based on modern coding theory, in particular sparse-graph codes and its analysis tools, thus shifting from the current research paradigm based on algebraic block codes. We believe that sparse-graph codes are excellent candidates to fulfill the stringent requirements of next-generation DS systems in terms of efficiency, reliability, flexibility and low-complexity.

Popular scientific description (Swedish)*

Vi lever i en tid av dataöversvämning, med en explosion av tjänster och applikationer som till exempel sociala nätverk, videoströmning och molntjänster. Med den kraftiga ökningen av dessa tillämpningar kommer den stora utmaningen att globalt dela, lagra, bearbeta och leverera stora mängder information. Enligt färska beräkningar växer mängden digital information som genereras med en takt på 40% per år. Den globala mobila datatrafiken ökade 69% under 2014 och förväntas fortsätta att öka.

Utformningen av effektiva och pålitliga lagrings- och leveranssystem för att klara av denna aldrig tidigare skådat flöde av information är en av de grundläggande utmaningarna för vår generation och har gett upphov till det växande forskningsområdet distribuerad lagring (DL). Tänk på Dropbox, som lagrar några av våra mest värdefulla filer. Självklart vill vi att vår information ska lagras på ett tillförlitligt sätt så att den inte går förlorad. Att bygga en ensamstående hårdvara med tillräcklig lagringskapacitet för att klara stora datamängder skulle vara extremt dyrt. Huvudtanken bakom DL är att erbjuda ett betydligt billigare alternativ: att samla resurser från flera billiga sammankopplade lagringsenheter (så kallade lagringsnoder). Informationen distribueras sedan över dessa sammankopplade lagringsnoder, som tillsammans ger den önskade tillförlitligheten.

DL-system finns i många varianter, exempelvis datacenter, backup-system och molnlagringsnätverk, som vi kallar trådbunden DL. På senare tid har DL utvidgats till datalagring över mobila enheter i ett nät, vilket kallas trådlös DL. Det huvudsakliga syftet med trådlös DL är inte att lagra information för att bevara den över tid och att minska dess lagringskostnad, som i trådbunden DL, utan att föra innehållet närmare slutanvändaren för att undvika den trådlösa förbindelsen för datahungriga applikationer såsom videoströmning.

Både trådbunden och trådlös DL delar en gemensam egenskap: lagringsnoder kan gå sönder. Eftersom lagringsnoder är billiga i trådbunden DL är det snarare en regel än ett undantag att enskilda noder går sönder. Dessutom kan de bli otillgängliga på grund av omstarter i systemet, lokala strömavbrott och underhållsverksamhet. I trådlös DL kan en mobil nod helt enkelt lämna nätverket eller vara otillgänglig under en tid. En viktig egenskap hos DL-system är därför att vara robusta mot att noder går sönder permanent och mot kortfristiga avbrott för att förbättra tillförlitligheten.

Det enklaste sättet att uppnå tillförlitlighet är repetering. Vi kan till exempel kopiera informationen och lagra tre kopior i tre olika lagringsnoder. Eftersom den ursprungliga informationen kan utvinnas från någon av de tre kopiorna kan systemet tolerera att upp till två noder går sönder samtidigt. Repetering är ineffektivt när det gäller lagringsutrymme: av de tre kopiorna består två av redundans.

Ett mer effektivt sätt att lagra information i distribuerade system än en enkel repetering tillhandahålls av felrättande koder. Huvudtanken bakom felrättande koder i DL är att införa redundans så att informationen kan rekonstrueras genom att läsa en delmängd av lagringsnoderna. Informationen som ska lagras delas först upp i k symboler, som sedan kodas av en (n, k) felrättande kod till en längre sekvens av n > k symboler, vilket inför redundans. De n kodsymbolerna lagras typiskt i n olika lagringsnoder. De extra n - k lagringsnoderna kan hjälpa till att återvinna den ursprungliga informationen i fall några av de n lagringsnoderna går sönder.

Nuvarande kodkonstruktioner som är baserade på algebraiska blockkoder kan inte möta de framtida kraven på tillförlitlighet och lagringseffektivitet inom datalagring. Ett citerat av gästredaktören för JSAC specialnummer 2014 om nästa generations lagringssystem är: "datacenter och molnlagringssystem behöver desperat nya metoder för att förbättra lagringseffektiviteten och dataöverföringshastigheterna". Forskning inom trådlös DL är i ett ännu tidigare skede och inga praktiska kodningsmetoder har än så länge föreslagits.

Detta projekt behandlar dessa grundläggande öppna forskningsproblem med hjälp av modern kodningsteori, framför allt genom att använda glesa grafkoder och deras analysverktyg. Vi tror att glesa grafkoder, som är kända för att vara exceptionellt bra i många andra kommunikationsproblem, kan uppfylla de stränga kraven på hög tillförlitlighet, låg lagringseffektivitet och flexibilitet, med rimlig komplexitet, i framtida DL system.

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

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

Keyword 1*

Distributed storage

Keyword 2*

Modern coding theory

Keyword 3*

Sparse-graph codes

Keyword 4

Erasure correcting codes

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 are no ethical issues in this research plan.

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

Rethinking Distributed Storage Based on Sparse-Graph Codes

Alexandre Graell i Amat and Fredrik Brännström

1 Purpose and Aims

The recent years have witnessed the explosion of services and applications such as social and media networks, video streaming, and cloud computing. With the surge of these applications comes the grand challenge to globally share, store, process and deliver massive amounts of data. According to recent estimates, the amount of digital data generated grows at a rate of 40% per year, a factor of 30 by 2025 [1]. The global mobile data traffic grew 69% in 2014, and is expected to keep increasing [2].

The design of efficient and reliable storage and delivery systems to cope with this unprecedented deluge of data is one of the fundamental challenges of our generation and has given rise to the emerging research area of **distributed storage (DS)**, where data is stored over multiple individually unreliable storage nodes to globally provide reliability. DS systems come in many flavors, such as data centers, peer-to-peer (P2P) backup systems and cloud storage networks, which we group under the label of **wired DS**. More recently, DS has been extended to data storage across mobile devices in a cellular network, which we refer to as **wireless DS**. All these applications share a common characteristic: storage nodes may fail (or simply leave the system permanently in P2P systems or a cellular network), or become inaccessible due to machine reboots, local power outages, and maintenance operations. Therefore, **resilience to permanent node failures and short-term outages to improve reliability is an essential property of DS systems**.

The prevailing research paradigm is based on short algebraic block codes, which provide reliability by encoding data across a rather small number of storage nodes, typically 10-20, at the expense of storage overhead. However, to meet the increasing demands of data storage and allow the continued development of existing and new applications, devising more reliable and, even more importantly, more storage-efficient (in terms of storage overhead to keep the storage cost low) DS systems is paramount. The only viable way to increase storage efficiency (i.e., reduce storage overhead) and/or reliability is to increase the code length. That is, to store across more storage nodes. Unfortunately, the complexity of algebraic block codes increases exponentially with the code length [3], thus they are not suited to address future needs. Moreover, for algebraic block codes, the change of code parameters to yield flexibility in terms of reliability and/or storage overhead, a desirable property for next-generation DS systems, requires the transmission of significant amounts of data within the DS network [4]. Research on wireless DS is at an even earlier stage, and no practical coding schemes are yet available. Therefore, novel code designs are desperately needed that leap ahead of the incremental developments of current approaches.

In this project, **we address this gap in research by resorting to modern coding theory, in particular sparse-graph codes and their analysis tools**. We believe that sparse-graph codes, which are known to perform exceptionally well in a number of communication problems, can fulfil the stringent requirements of high reliability, low storage overhead and flexibility, with reasonable complexity, of future DS systems.

1.1 Specific Project Goals

The purpose of this project is to **investigate, understand, and design flexible sparse-graph codes with efficient decoding algorithms for next generation DS systems**, targeting both wired and wireless storage networks. The innovative contributions of this project are to:

- Gain a fundamental understanding of the connection between the parameters of a sparse-graph code, the allocation of the code symbols to storage nodes, and the main performance metrics of a DS system: resilience to failures, storage overhead, repair cost of a storage node and complexity.
- Based on this understanding, develop novel sparse-graph codes with good reliability, low storage overhead and complexity, and flexibility, as an attractive alternative to existing algebraic solutions.
- Address the fundamental question of, given a code family, determining the optimal node repair strategy, in terms of communication cost and complexity.

- Develop novel joint storage and delivery strategies for wireless DS using sparse-graph codes, under given data download and repair rates.

Our research falls into the category of fundamental research. However, it is highly motivated by practical concerns. To face the challenge of efficiently store and deliver the ever increasing deluge of data of modern societies, next-generation DS systems call for radically new approaches, since the current ones, based on algebraic block codes, are not scalable. This leaves room for groundbreaking contributions, and we believe that the proposed research, which rethinks current DS systems in a longer-time horizon, is very timely and has high potential impact.

2 Survey of the Field

Originally, the concept of DS was born to provide reliable, cost-efficient storage solutions for large data centers. Building single pieces of reliable hardware with enough storage capacity to cope with massive volumes of data would be extremely expensive, if not impossible. The idea of DS is to connect together **multiple inexpensive storage units (referred to as *storage nodes*) to provide reliability globally**. The **data is then stored in a *distributed* fashion across these interconnected storage nodes**, thus the name of DS. Today, DS covers a broader range of applications, which include cloud storage networks and P2P storage/backup systems that use nodes across the Internet for distributed file storage. Together with DS for data centers, we can group these applications under the umbrella of wired DS. Examples of such systems are the Google File System (GFS) [5], Facebook's Hadoop distributed file system (HDFS) [6], and Microsoft's Windows Azure cloud system [7]. More recently, DS has also been proposed for wireless networks [8–10]. The main purpose of wireless DS is not to reduce the storage cost, but to bring content closer to the end user to avoid the wireless bandwidth bottleneck for data-hungry applications, such as video streaming.

In all these scenarios, **guaranteeing reliability requires the introduction of redundancy**, since individual nodes are prone to failures (or may simply leave the system in wireless DS). Therefore, resilience to failures (also called **fault tolerance**) is a fundamental requirement for DS systems. Traditionally, fault tolerance has been achieved by simple replication of the data across multiple storage nodes. For instance, the GFS and HDFS store three copies of the original data. Since the data can be recovered from any of the three copies, the system can tolerate up to two node failures. However, replication is largely inefficient in terms of storage space, since it introduces a large storage overhead. Therefore, DS systems are increasingly using more sophisticated **erasure correcting codes** [6, 7].

The main idea behind erasure correcting coding in DS is to introduce redundancy so that data can be reconstructed by reading a subset of storage nodes. A piece of data is divided into k (nonbinary) symbols, which are encoded by an (n,k) (nonbinary) erasure correcting code into a longer sequence of $n > k$ symbols, thus introducing redundancy. The n code symbols are typically stored in n different storage nodes. The additional $n-k$ storage nodes help in recovering the original data in the case some of the n storage nodes fail. That is, data can be reconstructed by reading a subset of storage nodes. The storage efficiency is measured in terms of the **storage overhead**, defined as n/k. Codes achieving the best tradeoff between fault tolerance and storage overhead, called maximum distance separable (MDS) codes (e.g., Reed-Solomon codes), tolerate up to $n-k$ failures [3]. This means that the original data can be recovered from any subset of k storage nodes. Erasure correcting codes provide a more efficient way to store data in distributed systems than simple replication. For instance, if the system needs to tolerate 2 failures, a $(6,4)$ MDS code provides the same fault tolerance of 3-replication with a storage overhead of $n/k = 1.5$ in contrast of $n/k = 3$ for 3-replication. To achieve this saving in storage overhead, data needs to be stored across a larger number of storage nodes (6 instead of 3). For a given fault tolerance, increasing n (the code length) yields a lower storage overhead. Alternatively, for the same overhead, the use of a longer code achieves higher fault tolerance. State-of-the-art wired DS systems use replication or short algebraic block codes. For example, around 92% of Facebook log files is stored using 3-replication and the rest using the $(14,10)$ Reed-Solomon code [11].

In addition to fault tolerance, coding also provides a faster content download, i.e., it improves content accessibility, because content download is accomplished from a subset of the storage nodes, therefore several requests can be handled in parallel [12].

Besides **fault tolerance** and **storage overhead**, there are several other performance metrics and tradeoffs that must be considered in a DS system. To enable long-term data availability, whenever a node fails (or leaves the system in wireless DS), a new node needs to be added and populated with data so that the initial state of reliability is preserved. This problem is known as the **repair problem** [13], and gives rise to two important performance metrics, **repair bandwidth** (the amount of information (in bytes) communicated during the repair of a failed node) and **repair access** (the number of nodes involved in the repair of a failed node). Bandwidth is a costly resource in wired DS and even more critical in wireless DS. Moreover, a high repair bandwidth increases the time that the erased information is not accessible. In some applications such as data centers, accessing the information can also be costly, thus the repair access is as well an important performance metric [14].

One of the main problems of using classical MDS codes is that repairing the lost data requires the retrieval of large amounts of data from large subsets of nodes. This has spurred a great deal of research on codes addressing the repair problem. Regenerating codes [13, 15, 16] were the first family of a new wave of codes especially designed to minimize the repair bandwidth associated to the repair of a single node. These codes address the repair problem by describing an optimal storage-repair bandwidth tradeoff. However, the repair process requires contacting a large subset of nodes, which complicates the design of the system and increases the number of required read/write operations, a bottleneck in wired DS [14]. Other code constructions aiming at reducing the repair bandwidth are the MDR codes [17], Zigzag codes [18] and piggyback codes [19]. A different line of codes, called locally repairable codes [11, 20], and local reconstruction codes (LRC) [7, 14] aim at reducing the repair access at the cost of a higher storage overhead. These code designs are algebraic constructions: they start from an MDS code and try to reduce the repair access by slightly modifying the code.

Other important performance metrics are **download** (retrieval of the data from the DS system) **complexity**, and **flexibility**. These performance metrics, which only very recently are starting to be considered in the literature, are discussed in more detail below for wired and wireless DS.

2.1 Wired Distributed Storage

Current research on DS [7, 11, 13–20], discussed above, is based on short algebraic block codes. In practice, this means that while DS systems contain a large number of storage nodes (tens of thousands in the case of a data center), data is encoded across only a small number of these nodes. In other words, the storage network is subdivided into small independent subnetworks. This approach fulfils current storage needs in terms of fault tolerance and storage overhead, while keeping repair access and bandwidth relatively low. However, the data to be stored grows much faster than the available storage capacity [21], as shown in Fig. 1. A non-negligible fraction of this data requires a high level of protection to ensure its availability over a long period of time. Therefore, in order to meet future storage needs, fault tolerance and especially storage overhead become even more stringent parameters.

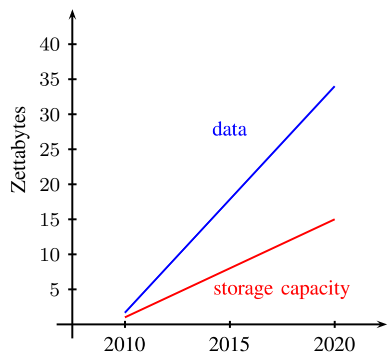

Figure 1: Estimation of produced data growth versus available storage capacity growth [21].

As discussed earlier, to decrease the storage overhead (and/or increase fault tolerance) a longer code needs to be used. A naïve approach would be to consider one of the existing code designs [7, 11, 13–20] and apply it to a longer code length. Unfortunately, the decoding complexity of algebraic block codes increases exponentially with the code length [3], which would make the cost of download and in particular of repair unacceptable. For instance, the time needed to complete a repair increases with the decoding complexity. During this time the storage nodes involved in the repair are not accessible to other processes. Moreover, it makes the system more vulnerable to other failures, which is particularly critical in the event of correlated failures. Thus, code constructions based on algebraic block codes are **unsuited to face the future requirements of data storage in terms of reliability and storage overhead**. This poses a **significant challenge, since novel solutions are required**. Quoting the Guest Editorial of the 2014 JSAC special issue on next-generation storage systems, "data centers and cloud storage systems desperately need new methods to improve storage efficiency and data transfer speeds" [22]. This project addresses this fundamental open problem.

An alternative to algebraic block codes are sparse-graph codes [3]. Sparse-graph codes, such as low-density parity-check (LDPC) codes [23], have a decoding complexity that grows linearly with the code length. Surprisingly, there are very few works on sparse-graph codes in the context of DS, perhaps because research in this area has been addressed so far by the information theory and algebraic coding theory communities. The application of LDPC codes to DS systems was first studied in [24, 25]. However, these works considered off-the-shelf codes, and did not proposed specific designs for DS. Therefore they did not generate much interest in the scientific community. The only (very recent) coding schemes based on sparse-graph codes are the repairable fountain codes [26] and the LDPC codes for 2D arrays in [27]. In [26], only a probabilistic analysis is performed, and no explicit construction is provided, while [27] focuses on small networks and assumes a very particular and unconventional failure model where only part of the data in a failed node is not accessible.

Another relevant feature of next-generation DS systems is flexibility. For example, one would like to change the parameters (n, k) to increase the accessibility level for one particular piece of stored data when a file becomes more popular. **Current DS systems are fixed** and state-of-the-art coding schemes for DS **lack flexibility**. The only work addressing flexibility in DS is [4], where the cost (in terms of the amount of data that needs to be transmitted within the DS network) of changing code parameters was considered. While [4] provides some insight, a more thorough analysis is necessary and the optimal tradeoffs are still to be formulated.

We believe that, thanks to their low complexity and flexibility, sparse-graph codes are excellent candidates for future DS systems, and this observation constitutes one of the pillars of this proposal.

2.2 Wireless Distributed Storage

The steadily increase in demand for downloading higher quality content to wireless devices, threatens to completely congest the already overused wireless networks. Wireless DS tackles this problem by replacing backhaul capacity with storage capacity close to the end users to store files (e.g., popular video files). Here the main purpose is not the storage of the data to preserve it over time, as in wired DS, but to store data closer to the end users to deliver the content more efficiently. Therefore, the primary goal is not storage overhead (since there is less data to be stored, the storage overhead becomes less critical), but the **delivery phase (the download)** becomes vital, since bandwidth is a shared scarce resource. The seminal work by Dimakis *et al.* on regenerating codes [13] mentioned both wired and wireless DS in its introduction. Indeed, the main parameter that regenerating codes address, the repair bandwidth, is of crucial importance for wireless DS. However, since then, the main bulk of research on DS has been focused on wired DS, while **research on wireless DS is still at a very early stage, and very few papers have specifically addressed this scenario**.

A line of work on wireless DS [8–10] considers the storage of data directly on the mobile user devices, exploiting the large storage capacity available on modern smartphones and tablets, and device-to-device (D2D) communication. In this way, a set of mobile devices within a distance from each other form a storage community, a local DS network. The devices (storage nodes) are preloaded with data by the base station (BS) in an offline fashion during a placement phase, e.g., during a period of low network load. A fundamental difference with respect to wired DS is that the download of the data can be done not only from the storage nodes but, if necessary, the BS assists to deliver the files (or pieces of files) that cannot be downloaded from the DS network. In [8, 9], the placing of files in storage nodes to minimize the total average delay in the download phase was formulated as a linear program using replication and hypothetical *ideal* MDS rateless codes. However, no practical code designs are proposed. Moreover, the problem of node repair is not addressed in [8, 9]. The only paper addressing the repair problem is [10], where the authors analyzed the communication cost (in terms of transmit energy) incurred by data download and repair considering regenerating codes [13]. However, an infinite storage capacity in the mobile devices is assumed and instantaneous repair is considered. The first assumption is not realistic, and the second implies that the lost data due to node departure can be regenerated before another departure takes place, while in practice the system should be able to handle several node failures.

While the previous works above give very insightful results, the research in this area is still at a very early stage, and many open questions need to be addressed, such as a better understanding of the underlying tradeoffs and the design of practical coding schemes.

3 Project Description

The project is divided into four main tasks, as detailed below. A main emphasis is on sparse-graph codes, thus shifting from the mainstream of research. Tasks 1 and 2 are devoted to wired DS, while Task 3 focuses on wireless DS. Task 4 spans both wired and wireless DS. Our methods are mathematical analysis supported by computer simulations. While the tasks will be carried out in a more or less chronological order, they are intimately linked to each other, thus we also expect that they will overlap over some periods of time.

Task 1. Connecting Sparse-Graph Code Parameters to Wired DS Performance Metrics

We aim to gain a fundamental understanding of the connection between the parameters of sparse-graph codes and DS performance metrics such as fault tolerance, storage overhead, repair access and repair bandwidth. Since considering the whole class of sparse-graph codes would be unrealistic, our main focus will be on spatially-coupled LDPC (SC-LDPC) codes [28], which are a new paradigm in modern coding theory. They achieve an outstanding erasure correcting performance and are characterized by a good locality (i.e., we expect them to yield a good repair access). Moreover, they are flexible in the code length. Thus, they are very promising candidates for flexible DS systems.

We will first consider binary SC-LDPC codes constructed from protographs [28], which are very attractive from a design perspective and allow for a high-speed hardware implementation. In the context of DS, the use of a binary code implies that several code bits are stored in each storage node. Thus, when a failure occurs, a block of bits is erased. This can be modeled by means of a block erasure channel (BLEC). The asymptotic performance (when the code length goes to infinity) of sparse-graph codes on the BLEC can be analyzed using density evolution (DE) [29]. The asymptotic analysis is a useful tool in modern coding theory to determine good code ensembles. A code ensemble is a class of codes that share some common characteristics. Analyzing a specific code is very difficult, therefore typically one studies first a code ensemble and then finds good codes within these ensembles. The theory of SC-LDPC codes is very rich for the binary erasure channel (BEC), but little is known about the BLEC. Using DE we will derive bounds on the block erasure probability (i.e., the fraction of node failures that can be tolerated) of SC-LDPC code ensembles as a function of the code parameters, namely base protograph and variable node (VN) and check node (CN) degrees. VN and CN degrees determine the code rate (hence the overhead) and also define the connectivity of the underlying bipartite graph, which we can link with the repair access and bandwidth. Therefore, this analysis will establish the tradeoffs between fault tolerance, storage overhead and repair access and bandwidth.

In a second phase, we will extend the analysis to nonbinary SC-LDPC codes, proposed and analyzed by the applicants in [30, 31] for the BEC. In this case, each code symbol is stored in a single storage node and the channel model is a symbol erasure channel. Nonbinary SC-LDPC codes simplify the allocation of code symbols to storage nodes, and can potentially outperform their binary counterparts, at the expense of an increase in complexity, which will be carefully evaluated in Task 4.

To achieve flexibility we will also investigate the construction of (binary and nonbinary) rate-compatible SC-LDPC code ensembles over the BLEC, and extend the analysis to these ensembles.

Outcomes: An analytical framework to link code parameters (base protograph, node degrees, etc.) with DS performance metrics, and determine a number of promising code ensembles.

Task 2. Sparse-Graph Code Designs for Wired DS

This task naturally follows Task 1 and is devoted to the design of practical sparse-graph codes for finite length (i.e., a finite number of storage nodes) within the most promising code ensembles found in Task 1. As opposed to algebraic block codes, the recoverability of the data when a sparse-graph code is used depends not only on the number of failures in the DS system, but also on the failure pattern. In other words, for a certain number of failures, the recoverability can only be guaranteed with a certain probability, while we would like to have full guarantee of a certain fault tolerance. This is due to the suboptimality of the (low-complexity) iterative decoding of sparse-graph codes, which is dominated by certain harmful substructures in the graph, called *stopping sets* [32], that make the decoding fail. As a result, two particular codes from the same code ensemble may perform differently. To guarantee a given fault tolerance, a careful joint design of the code and the allocation of the encoded symbols to storage nodes must be performed, such that harmful stopping sets of a given size can be avoided. We will make use of stopping sets enumeration tools [33] to find good codes within the ensembles of Task 1 that avoid small stopping sets. Then, we will devise allocation strategies to allocate symbols belonging to the same stopping sets over different storage nodes to guarantee a certain fault tolerance. Note that the allocation will also have an influence on the repair access, and this must be considered in the design. By means of this joint design approach, we will be able to combine the benefits of sparse-graph codes in terms of low complexity and flexibility with a fault tolerance guarantee.

We will also address the design of sparse-graph codes that keep some level of compatibility with current DS topologies. As discussed in Section 2.1, a DS network is typically divided into small independent subnetworks, each protected by a short block code. We propose to connect several subnetworks to form a so-called generalized LDPC (G-LDPC) code [3]. That is, we build a sparse-graph structure on top of the individual short block codes that protect each subnetwork. G-LDPC codes are LDPC codes where the CNs are stronger block codes, as opposed to single parity-checks. We will analyze the tradeoffs between fault tolerance and storage overhead by considering several block codes as component codes for each subnetwork. A stronger component code brings higher reliability within the subnetwork but entails a higher local complexity, while weaker codes require the connection of more subnetworks, i.e., a larger G-LDPC code.

Outcomes: Low-complexity sparse-graph codes with good tradeoff between fault tolerance, storage overhead, and repair access/bandwidth. A design framework for G-LDPC codes in a DS setup, to enable a smooth evolution from current DS systems.

Task 3. Analysis and Design of Coding Schemes for Wireless DS

We will extend the analysis carried out in Task 1 to the wireless DS scenario where data is stored in mobile devices and D2D communication is used [8, 10]. The fact that data can be recovered from both the storage network and the BS (albeit at a higher communication cost) brings a new dimension to the problem. Furthermore, the download cost becomes a crucial parameter. We will consider a more realistic scenario than the one in [10] and assume that mobile devices have a finite storage capacity. For a given number of storage nodes, say n out of N mobile devices in a cell can store data, and a finite storage capacity in the devices, we will establish the connection between code parameters and the incurred repair bandwidth and download bandwidth (defined as the amount of information that needs to be transmitted for download). Note that in a wireless setting, the download phase is prone to errors due to channel outages. These can be interpreted as temporary node failures and must be included in the analysis. If the outage is long, the communication between the particular storage node and the user downloading its data must be considered lost.

We will consider two approaches. First, we will consider the common approach where the placement of the data to the storage nodes is treated separately from the delivery phase [10]. We will analyze regenerating codes, as in [10], and other algebraic block codes, and then extend the analysis to the sparse-graph code families in Task 1. We will also consider a joint storage/delivery approach, as advocated in [8], where files are encoded by the BS using a hypothetical *ideal* MDS rateless code. A rateless code [34] is a class of sparse-graph codes that encodes a sequence of k information symbols to a potentially unlimited stream of coded symbols, which are obtained as linear combinations

of the k information symbols. Each storage node is then populated by (possibly different) coded symbols. A file can then be retrieved provided that any $k' > k$ coded symbols are recovered from any storage node. This is an interesting approach because if the link between a user downloading a file from the storage network and a particular storage node is lost, the coded symbols already downloaded from this storage node are useful to recover the entire file (and the used bandwidth is therefore not wasted). For block codes, on the contrary, the whole data stored in a node must be downloaded to be useful. However, no practical code schemes were proposed in [8] (the use of ideal codes served to derive information-theoretic results) and the repair problem was not considered. Furthermore, uncoded transmission from the mobile devices is assumed. We will generalize this scheme and assume that a rateless code is also used by the mobile devices. We will analyze and design practical two-layer rateless codes (both at the BS and the devices). Using DE, for a given number of storage nodes and finite storage capacity in the devices, we will optimize the degree distributions at the BS and the storage devices to minimize the overall communication cost.
Outcomes: A fundamental understanding of the connection between code parameters to wireless DS performance metrics. Novel practical sparse-graph coding strategies for joint storage and delivery.

Task 4. Optimal Repair Strategies and Communication Cost and Complexity Analysis

This task will be devoted to devise optimal repair strategies and to an analysis of the communication cost and complexity of the repair and download processes as a function of the node failure and download rates. Furthermore, we will analyze the cost associated to a change of storage parameters in the flexible systems developed in Tasks 1-3.

In today's DS systems, the repair of each failed node is mostly treated instantaneously and independently of others. This approach may be appropriate if short algebraic block codes are used, since they can tolerate only a small number of failures (typically 2-3). Therefore, if a node failure occurs, it needs to be handled immediately to avoid data loss. However, if stronger erasure correcting codes are used, the current repair paradigm may not be the optimal one, and dealing with a certain number of node failures at once may be beneficial. Our preliminary analytical results for a simple wireless DS scenario and short block codes [35] (see Section 5) show that the overall communication cost in terms of transmit energy, which is proportional to the amount of information that needs to be communicated during repair and download, can be minimized if a proper repair scheduling is applied. In particular, we introduced a periodic repair scheme and showed that instantaneous repair is not always optimal. We will extend this analysis to more realistic wireless DS networks to devise optimal repair schedules. We will also consider wired DS and address the following fundamental question: given a code family, which is the optimal (in terms of communication cost and complexity) number of node failures that should be repaired jointly? We will consider first MDS codes, and algebraic block codes in the literature [11, 13–20], which are easier to analyze. We will then analyze the sparse-graph codes developed in Tasks 1-3. This analysis will allow us to compare different code structures and find the optimal operating points (for example, for a given storage overhead, in terms of overall cost it may be beneficial to increase the code length –thus fault tolerance– and treat several node failures jointly).

We will also perform an analysis of the cost incurred by changing storage parameter (n, k) in terms of the amount of data that needs to be communicated within the DS network. The only work available in the literature is [4] for a simple network topology. We will extend and refine this analysis to the flexible code structures proposed in Tasks 1-3. This task will be carried out partly in parallel with the other tasks, and conclusions will be fed back to them.
Outcomes: A thorough understanding of the repair problem and the derivation of optimal (in terms of communication cost and complexity) repairing strategies. An analysis of the overall communication cost (repair and download) and the cost incurred by changing storage parameters.

3.1 Some Limitations

Storing data in DS systems and even untrusted wireless devices in wireless DS brings novel challenges regarding security and data integrity. For example, an adversary may corrupt a large amount of stored data simply by altering the data stored on a small number of storage nodes. Eavesdropping to the data becomes easier because of multiple downloads during node repair. In this project we do not consider security aspects, as this would be unrealistic within the lifespan of the project. However, research on this topic is already under progress in another project (see Section 6), and interactions/synergies between the two projects may arise.

For wireless DS we study the case where data is stored in the mobile devices and D2D communication is exploited, as in [8–10]. A second line of work [36–38] considers the deployment of wireless access points, called *helper nodes*, with a large storage capacity and only wireless connectivity. This approach is similar to the one in [8, 9] but requires additional infrastructure. All these works are aimed at the derivation of information-theoretic limits, while no practical, low complexity schemes are proposed. Due to the limited lifespan of the project, we do not consider this architecture here, but we believe that our research in Tasks 3 and 4 can also bring new insights for this scenario.

Finally, we will perform no testbed experiments. However, the most promising coding schemes developed within this project may be experimentally tested using the DS platform of the startup company ENVOR Technologie, co-founded by one of our international collaborators (see Section 6).

4 Significance

DS is a research area that has virtually exploded in the recent years and a new frontier in coding theory, with many open challenges to be addressed. Coding in this area is relatively immature as compared to wireless communications and classical storage problems. The current research paradigm is based on short algebraic block codes. For wired DS, the extraordinary increase in data storage demands, fueled by the deluge of applications such as cloud computing, brings even more stringent requirements in terms of fault tolerance and storage overhead. The high complexity of algebraic block codes for large code lengths makes them unsuited to face these requirements. For wireless DS, the steadily increasing demand for downloading higher quality content to wireless devices threatens to congest the wireless network. Research on wireless DS to cope with this challenge is at an even earlier stage, and has been mainly addressed from an information theory point of view, while no practical low-complexity coding schemes are available yet.

The application of modern coding theory in DS seems to be a natural step to be taken. The lower complexity and flexibility of sparse-graph codes, as compared to algebraic block codes, makes them excellent candidates to provide highly reliable, efficient storage and delivery solutions at low cost. Surprisingly, almost no research in this area has been conducted so far, perhaps because the *spatial coupling* of LDPC codes, the new paradigm in modern coding theory, is attracting the attention of most modern coding theorists (including ourselves). Based on these facts, we believe that the proposed project, which **rethinks DS systems in a longer-time horizon**, and finds its roots in modern coding theory, brings a novel approach, is very timely, and has a great potential to deliver results with significant impact.

The team behind this proposal, with its strong expertise in modern coding theory (Prof. Graell i Amat) and complexity issues for practical implementation (Prof. Brännström), together with its international collaborators (see Section 6), who bring a strong background in algebraic coding theory, are well positioned to successfully address the challenging topics of this proposal.

5 Preliminary Results

DS is an emerging research area and our interest in the topic was ignited mid 2014 during a research visit of the main applicant at CNRS/ENSEA, hosted by his international collaborator Prof. Iryna Andriyanova. Since then, we have been working on the topic and Prof. Andriyanova is currently spending her sabbatical in our research group (see Section 6). We have already done some interesting preliminary work, which we briefly summarize in the following. This work provides a solid basis for the suggested project.

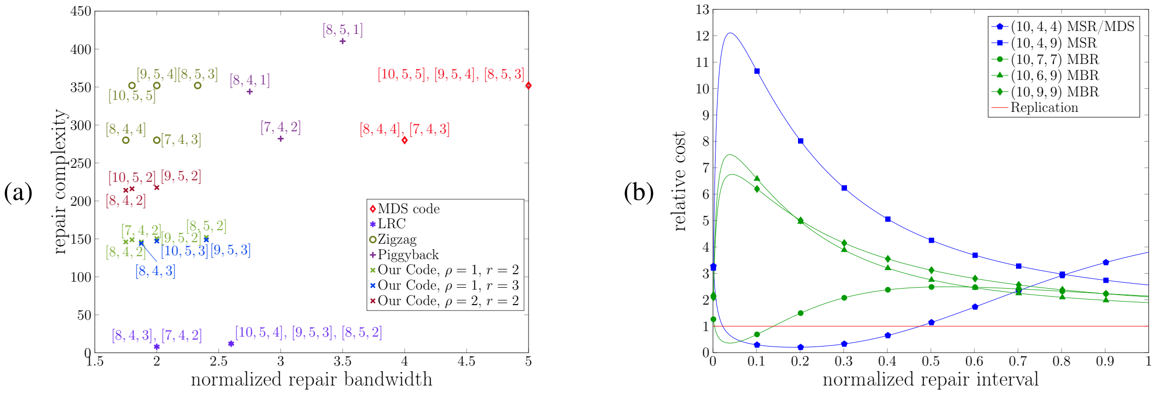

Figure 2: (a) Repair bandwidth (normalized by the size of a data block) and repair complexity for several codes. The parameters $[n,k,t]$ denote code length, information block length, and fault tolerance, respectively. (b) Cost relative to replication cost as a function of the repair interval (normalized to the average node lifetime). The parameters (n,k,d) denote code length, information block length, and repair access, respectively.

Wired DS. In a very recent work [39], we investigated the complexity of the repair process. We proposed a new code construction that achieves low repair bandwidth and low repair complexity. In particular, we proposed a family of block codes with two classes of parity nodes. The primary goal of the first class of nodes is to provide a good erasure correcting capability, while the second class facilitates node repair, reducing the repair bandwidth and repair complexity. Fig. 2(a) compares the repair bandwidth and repair complexity (in terms of number of equivalent binary additions to repair a data block) of the proposed codes with other codes in the literature. The proposed codes achieve significantly better repair bandwidth and complexity with respect to piggyback codes [19], and better repair complexity than Zigzag codes [18], at the expense of a slightly lower fault tolerance. LRC [7] perform best in terms of repair complexity, but our codes yield better repair bandwidth (we remark that when the size of a block is large –it can be in the order of terabytes– the gain in repair bandwidth is very significant). The proposed code construction is based on short block codes. However, we believe that this concept (using different classes of nodes) can be generalized to longer code lengths and to a sparse-graph code scenario.

Wireless DS. In [35] we examined a wireless DS network (similar to the scenario in [10]) where mobile devices roam in and out of a cell. The expected number of devices in the system is 100 and a maximum of 10 devices can store data. For a finite storage capacity and a scheduled repair (i.e., we relax the infinite storage capacity and instantaneous repair assumptions in [10]) we derived analytical expressions for the repair and delivery communication cost when short block codes (MDS and the MBR and MSR codes in [13]) are used. In Fig. 2(b) we plot the communication cost in transmit energy (proportional to the amount of information that needs to be communicated during repair and download) relative to the cost incurred by replication as a function of the repair interval for several codes. Despite the fact of considering a simple scenario, our preliminary investigations revealed interesting and somewhat unexpected results, in contrast with [10]. For instance, the results suggest that MDS codes, which are known to suffer from a high repair cost, yield the lowest cost for some repair frequencies. They also rise interesting questions and tradeoffs on repair/delivery bandwidth, fault tolerance and repair access, which we will address in the proposed project.

6 International and National Collaboration

International collaboration is essential for our research. The main applicant and the co-applicant have a long history of international cooperation and exchange. We have ongoing collaborations in the field of DS with the Simula Research Lab/University of Bergen (UoB), Bergen, Norway (Dr. Eirik Rosnes) and with CNRS/ENSEA (Prof. Iryna Andriyanova), Paris Area, France. In particular, Prof. Graell i Amat is an International Partner of the project “Reliable and Secure Distributed Storage” (2015–2018), funded by the Research Council of Norway and led by Dr. Rosnes. Within this project, Prof. Graell i Amat will co-supervise a PhD student (starting September 2015) together with Dr. Rosnes on secure DS. This project also covers short research visits (1 month per year in each direction). Prof. Andriyanova has a strong expertise in DS and is co-founder and technical advisor of the startup ENVOR Technologie, that designs DS software for data centers. She is spending her sabbatical at Chalmers (January-June 2015) working with us on DS, and Prof. Graell i Amat will visit CNRS/ENSEA for 2 months in Fall 2015 within the framework of a CNRS grant.

Moreover, Prof. Graell i Amat has ongoing collaborations on several facets of sparse-graph codes with some of the leading researchers in this field: Prof. Daniel J. Costello, Jr. (University of Notre Dame, USA); Prof. Henry Pfister (Duke University, USA), Dr. Gianluigi Liva (German Aerospace Center, DLR, from which he has been recently awarded a Senior Scientist Fellowship for a 3-month research visit (see CV)); Prof. Michael Lentmaier (Lund University, Sweden).

This work will be carried out in close collaboration with Dr. Rosnes and Prof. Andriyanova. The expertise in algebraic coding theory at Simula/UoB is likely to become very valuable to this project. The student hired in this project will spend research visits at UoB and ENSEA/CNRS during the course of the proposed project. We also plan that the new PhD student will spend a few months in another internationally recognized research group abroad.

7 Other Grants

The main applicant's present VR funding consists of the grant 2011-5961 (detailed in the report), which expires this year. There is no overlap between this grant and the present application.

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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

Scientific Report

1. Project Information

The project "Signal Recovery: Compressed Sensing meets Coding Theory" (dnr. 2011-5961), with sole applicant Prof. Alexandre Graell i Amat, was approved for the period Jan 1, 2012, to Dec. 31, 2015. The funding received (3280 kSEK) has partially supported Prof. Graell i Amat and PhD student Christian Häger.

I was hired by the Department of Signals and Systems at Chalmers as an Assist. Prof. early 2011, on funds mainly supplied by another project. For reasons out of our direct control, the funding initially allocated to cover my salary disappeared in 2012. Thus, in agreement with the Head of the Division of Communications Systems, the funds for 2011-5961, which were initially intended to fund a PhD student on compressed sensing, were re-allocated to cover my ongoing research activities on modern coding theory and to partially cover PhD student Häger, whom we hired in Sep 2011 on "modern coding theory applied to optical communications" under my supervision. In addition to 2011-5961, Häger is funded by internal Chalmers funds for this research.

2. Scientific Results

The unwanted and unexpected topic shift for the 2011-5961 funds was obviously disappointing for us, but the research we undertook supported by 2011-5961 turned out to be very interesting, with some remarkable results that have resulted on several invited papers.

The scientific output within the framework of 2011-5961 funds has been quite large so far. The published papers (4 invited) are listed in Section 4 below.

In [1,11,13] ([11] is invited) we introduced and analyzed nonbinary spatially-coupled LDPC (SC-LDPC) codes. We proved that threshold saturation occurs for nonbinary SC-LDPC codes and showed that, contrary to uncoupled LDPC codes, the belief propagation threshold of nonbinary SC-LDPC codes improves with the field size and tends to the Shannon limit. This suggests the remarkable result that, with fix variable and check node degrees, capacity can be achieved by increasing the field size. We are currently working on the proof. We also showed that nonbinary SC-LDPC codes perform better than binary SC-LDPC codes for finite lengths.

In [9,10] ([9] is invited) we introduced the concept of spatially-coupled turbo codes (SC-TCs), as the turbo codes counterpart of SC-LDPC codes. For the binary erasure channel, we derived the exact density evolution to analyze their asymptotic behavior. We constructed a family of rate-compatible SC-TCs with very simple component encoders (i.e., low decoding complexity) that achieve close-to-capacity performance and very low error floors for a wide range of code rates.

In [4] we analyzed SC-LDPC codes for a relay channel with two sources and one relay (the extension to many sources and many relays is straightforward) and we proved that capacity can be achieved.

In [5] we designed optimal APSK constellations for a coherent fiber-optical communication system where nonlinear phase noise is the main impairment. Significant performance gains with respect to the state-of-the-art QAM constellations are achieved.

In [12] we studied SC-LDPC codes over a set of parallel bit channels and optimized the bit mapper to allocate the bits to the parallel channels. Parallel channels arise in many practical communication systems including multi-carrier transmission and bit-interleaved coded modulation (BICM). We also showed that, with a proper bit mapper optimization, a decoding wave effect can be initiated for tailbiting SC-LDPC codes. This opens the door to the use of talibiting SC-LDPC codes, which, until now, did not receive much attention because by default they do not experience the characteristic wave effect of terminated SC-LDPC codes that is at the basis of their outstanding performance. We then applied this concept in [2,3,6,8] to SC-LDPC codes with BICM for fiber-optical communications. The paper [8] was selected among the best ones in ECOC 2014 and we were invited to submit an extended version to the IEEE/OSA Journal of Lightwave Technology [2]. We have also an invited paper and talk on the topic in OECC 2015 [6].

In [7] we proposed an approach to finding good staircase code parameters based on density evolution. We also proposed an extension of staircase codes (a class of spatially coupled codes with hard decision decoding very promising for optical communications) that have steeper waterfall performance curves compared to those obtained from the original construction.

3. Relation to New Proposed Project

There is no overlap between the project 2011-5961 and this proposal. However, 2011-5961 provided the means to start up a collaboration with Prof. Iryna Andriyanova, ENSEA/CNRS, France, on SC-LDPC codes, a new paradigm in modern coding theory. In the framework of this collaboration, I visited ENSEA/CNRS several times. During these visits, our interest on distributed storage (DS) was ignited and we realized the high potential of modern coding theory on DS. This observation, together with our preliminary results, forms the basis of the proposed project.

4. Published Journal and Conference Papers Within the Project

Journal Papers

[1] I. Andriyanova, A. Graell i Amat, "Threshold Saturation for Nonbinary SC-LDPC Codes on the Binary Erasure Channel," *IEEE Trans. Inf. Theory*, second review round (minor revision).
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Conference Papers

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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	Alexandre Graell i Amat	25
2	Participating researcher	Fredrik Brännström	15
3	PhD Student	New Student	100

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	2019	Total
1	Applicant	Alexandre Graell i Amat	25	252,000	261,000	270,000	280,000	1,063,000
2	Participating researcher	Fredrik Brännström	15	151,000	157,000	162,000	168,000	638,000
3	PhD Student	New Student	100	544,000	563,000	582,000	603,000	2,292,000
	Total			947,000	981,000	1,014,000	1,051,000	3,993,000

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	68,000	71,000	73,000	76,000	288,000
	Total	68,000	71,000	73,000	76,000	288,000

Running Costs

	Running Cost	Description	2016	2017	2018	2019	Total
1	Computers	(one laptop per participant)	60,000				60,000
2	Conferences	(1-2 per year)	30,000	60,000	60,000	60,000	210,000
3	Research visits	(1+1+4+2 months)	15,000	15,000	60,000	30,000	120,000
4	Defense	(compensation and travel costs for the opponent for Lic and PhD defense)		25,000		30,000	55,000
5	Publication costs	(overlength paper fees etc.)	5,000	10,000	10,000	10,000	35,000
6	IT	(computer cluster, software, and IT support)	21,000	22,000	22,000	23,000	88,000
	Total		131,000	132,000	152,000	153,000	568,000

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	947,000	981,000	1,014,000	1,051,000	3,993,000		3,993,000
Running costs	131,000	132,000	152,000	153,000	568,000		568,000
Depreciation costs					0		0
Premises	68,000	71,000	73,000	76,000	288,000		288,000
Subtotal	1,146,000	1,184,000	1,239,000	1,280,000	4,849,000	0	4,849,000
Indirect costs	348,000	360,000	372,000	385,000	1,465,000		1,465,000
Total project cost	1,494,000	1,544,000	1,611,000	1,665,000	6,314,000	0	6,314,000

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

The proposed project has a duration of 4 years, because this is the nominal duration of a PhD. The main applicant (Alexandre Graell i Amat) will participate in the project with 25% and the co-applicant (Fredrik Brännström) will participate with 15%. A new PhD student will be hired and spend 100% in the project (no teaching duties). The salaries include social fees of 51.0% and holiday supplement of 2.7%. At the department of Signals and Systems, Chalmers University of Technology, the indirect costs are 46.4% of the salaries, the IT costs (including computer cluster, software, and IT support) are 2.2% of the salaries, and the cost for premises is 7.2% of the salaries. One laptop per participant will be purchased in the beginning of the project (20 kSEK each). One conference trip the first year and two conference trips the following three years are planned, each with an estimated cost of 30 kSEK. A 1-month research visit to our international collaborators is planned for the PhD student in the first two years (15 kSEK each). In addition, the PhD student will go on a 4-month research visit after finishing the Lic.Eng. degree (60 kSEK) and on another 2-month reseach visit in the last year (20 kSEK). The cost for the opponent at the Lic and PhD defenses are covering flights, accommodation, and compensation. The publication costs for overlength papers etc are estimated to 5-10 kSEK per year.

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

Alexandre Graell i Amat – Curriculum Vitae

1 Higher Education Qualifications

- June 2001: **M.Sc. in Electrical Engineering,** Universitat Politècnica de Catalunya (UPC), Barcelona, Spain.
- Dec. 2000: **M.Sc. in Electrical Engineering,** Politecnico di Torino, Turin, Italy.

2 Doctoral Degree

- March 2004: **Ph.D. in Electrical Engineering, Area: Coding Theory,** Politecnico di Torino, Turin, Italy. **European Doctorate Award**. Dissertation title: "High-rate convolutional codes for high-speed concatenated codes applications: Design and efficient decoding". Advisor: Prof. Sergio Benedetto.
  Part of the Ph.D. (Sept. 2001 – May 2002) was pursued at the Center for Magnetic Recording Research, University of California San Diego (UCSD), CA, USA. Advisors: Jack K. Wolf and Paul. H. Siegel.

3 Postdoctoral Positions

- April 2004 – Dec. 2005: **Postdoc, Juan de la Cierva Fellow,** Universitat Pompeu Fabra, Department of Technology, Barcelona, Spain.
- April 2004 – Dec. 2005: **Postdoc,** Politecnico di Torino, Department of Electronics, Turin, Italy.

4 Qualifications Required for Appointment as a Docent

- June 2012: **Docent in Communication Systems,** Chalmers University of Technology.

5 Current Position

- Nov. 2013 – present: **Associate Professor**, Chalmers University of Technology, Department of Signals and Systems. 80% time devoted to research.

6 Previous Positions and Periods of Appointment

- Feb. 2011 – Oct. 2013: **Assistant Professor**, Chalmers University of Technology, Dept. of Signals and Systems.
- Oct. 2008 – Jan. 2011: **Associate Professor,** ENST Bretagne, Department of Electronics, Brest, France.
- Jan. 2007 – Dec. 2008: **Marie Curie Research Fellow,** ENST Bretagne, Department of Electronics, Brest, France.
- Jan. 2006 – Dec. 2006: **Research Fellow,** ENST Bretagne, Department of Electronics, Brest, France.
- Jan. 2001 – Dec. 2003: **Research Consultant,** STMicroelectronics, Data Storage Division, Milan, Italy.

7 Supervision

- **Postdoc supervision**: Dr. Amina Piemontese, May 2015–, (**main supervisor**).
- **Current PhD supervision**: Christian Häger, Chalmers, Sep. 2011–, (**main supervisor**); Khoa Quang Huynh, Chalmers, Sep. 2014–, (**main supervisor**); Alireza Sheikh, Chalmers, Oct. 2014–, (**main supervisor**); Mikhail Ivanov, Chalmers, May 2011–, (co-supervisor); Christopher Lindberg, Chalmers, Sep. 2012–, (co-supervisor); Saeedeh Moloudi, Lund, Sep. 2013–, (co-supervisor); Siddhartha Kumar, University of Bergen, Aug. 2015–, (co-supervisor);
- **Former PhD students**: Dr. Amina Piemontese, ENST Bretagne/Università di Parma, 2011, (**main supervisor**); Dr. Roua Youssef, ENST Bretagne, 2011, (**main supervisor**); Dr. Haïfa Farès, ENST Bretagne, 2011, (**main supervisor**); Dr. Nicolas Bitouzé, ENST Bretagne, 2013, (**main supervisor**); Dr. Behrooz Makki, Chalmers, 2013, (co-supervisor); Rajet Krishnan, Chalmers, 2015, (co-supervisor).

8 Honors and Awards

- 2015: **DLR–DAAD Senior Scientist Fellowship** by the German Aerospace Center (DLR) and the German Academic Exchange Service (DAAD) for a 3-month research visit at DLR, Munich, Germany.
- 2015: **CNRS Guest Professor Fellowship** by the Centre National de la Recherche Scientifique (CNRS), France, for a 2-month research visit to a CNRS research lab.
- 2014: **Nominated** (as one of three) for the Department of Signals and Systems' **Best Teacher** Award 2014.
- 2012 – 2013: **CNRS Guest Professor Fellowship** by CNRS for a 3-month research visit to a CNRS research lab.
- 2010: **2010 IEEE ComSoc Young Researcher Award for the Europe, Middle East and Africa Region**.
- April 2010: Appointed **IEEE Senior Member**.
- 2007 – 2008: **Marie Curie Intra-European Fellowship** by the European Commission.
- 2004 – 2006: **Juan de la Cierva Research Fellowship** by the Spanish Ministry of Science.
- 2001 – 2004: **Ph.D. Fellowship** by the Italian Ministry of Instruction, Universities and Research, and by STMicroelectronics.
- 2000: **Leonardo da Vinci Fellowship** by the European Commission.

9 Editorial Responsibilities and Conference Activities

- **Associate Editor**, IEEE Transactions on Communications (Nov. 2011–), IEEE Communications Letters (3 years, 2010–2013), European Transactions on Telecommunications (2 years, 2011–2013).
- **General Co-Chair**, 2016 European School of Information Theory, Gothenburg, Sweden, April 2016.
- **General Co-Chair**, 2013 Swedish Communication Technologies Workshop, Swe-CTW'13, Gothenburg, Sweden, August 27-31, 2013.
- **General Co-chair**, 7th International Symposium on Turbo Codes and Iterative Information Processing, ISTC'12, Gothenburg, Sweden, September 2012.
- **Organizing Committee Member (Conference Management)**, 6th International Symposium on Turbo Codes and Iterative Information Processing, ISTC'10, Brest, France, September 2010.
- **TPC Member (Selection)**, IEEE Int. Conf. Commun. (ICC), 2015; IEEE Global Commun. Conf. (GLOBECOM), 2009, 2014, 2015; IEEE Wir. Commun. & Networking Conf. (WCNC), 2011, 2013–2015; 6th Int. Symp. Turbo Codes & Iterative Inform. Processing (ISTC), 2010; IEEE Inform. Theory Workshop (ITW), 2009.

10 Awarded Research Grants as Main Applicant (Selection)

- 2015 – 2016: **European Commission – Marie Curie European Fellowship**. Title: "Distributed Storage Based on Coding". Amount: **186 kEUR**, (scientist in charge).
- 2012 – 2015: **Swedish Research Council – Project Research Grant for Junior Researcher**. Title: "Signal Recovery: Compressed Sensing meets Coding Theory." Amount: **3280 kSEK**, (main applicant).
- 2011 – 2013: **Swedish Foundation for Strategic Research – Research Mobility Programme "Gustaf Dalén"**. Title: "Cooperative Communications with Side Information". Amount: **100 kSEK**, (main applicant).
- 2011: **French & Norwegian Research Councils – Aurora Project**. Title: "Recovering the Unseen: Coding Theory Applied to Compressed Sensing". Amount: **12 kEUR** (France) + **120 kNOK** (Norway), (main applicant).
- 2009 – 2012: **Institut TELECOM – Futures et Ruptures Grant**. Title: "Acquisition parcimonieuse de données et théorie du codage: un croisement naturel". Amount: **111 kEUR**, (main applicant).
- 2008 – 2011: **NEWTEC, Belgium**. Title: "CPM with user interference cancellation for satellite access networks". Amount: **150 kEUR**, (main applicant).
- 2008 – 2010: **Pôle de Recherche Avancée en Communications (PRACOM)**. Title: "Joint channel and network coding for wireless networks". Amount: **100 kEUR**, (main applicant).
- 2008: **French & Italian Research Councils – Galileo Project**. Title: "Advanced channel coding and modulation for next generation wireless networks". Amount: **10 kEUR** (France) + **10 kEUR** (Italy), (main applicant).
- 2007 – 2008: **European Commission – Marie Curie Intra-European Fellowship**. Title: "Multi-application Advanced Channel Coding". Amount: **140 kEUR**, (main applicant).
- 2006 – 2007: **European Space Agency**. Title: "Study of enhanced digital transmission techniques for broadband satellite digital transmissions (BSDT)". Amount: **70 kEUR**, (main applicant).
- 2004 – 2006: **Spanish Ministry of Science – Juan de la Cierva Fellowship**. Title: "Analog decoding of concatenated codes". Amount: **91 kEUR**, (main applicant).

11 Assessment for Funding Bodies

- 2013: **Panel Member**, Swedish Research Council (VR), Panel NT-14 Signals and Systems.
- 2010: **International Reviewer**, French Research Cluster in Information & Communication Technologies and Sciences of Paris Île-de-France (Paris Region), France.
- 2010: **Panel Member**, CNRS Higher Education Excellence Chair "Communication theory and information theory", Centre National de la Recherche Scientifique (CNRS), France.

12 Further Information

- **Invited talks in conferences (2014–):** IEEE 20th OptoElectronics and Communications Conference, China, 2015; Workshop on "Recent Trends in Multiple Access for M2M", Serbia, 2015; 11th IEEE International Symposium on Wireless Communications Systems, Spain, 2014; XXXIth URSI General Assembly and Scientific Symposium, China, 2014; CNRS Workshop on "Spatially-coupled LDPC codes", France, 2014; Information Theory and Applications Workshop, 2009 – 2015, USA.
- **Scholarships and Travel Grants**: **Research Council of Norway – International Partner** (2015-2018), **Ericsson Research Foundation** (2014), **Adlerbert Research Foundation travel grant** (2014), **IEEE Travel Grant** (2001, 2004).
- **Licentiate Thesis Opponent,** Royal Institute of Technology (KTH), Stockholm, Sweden, June 2010.
- **Public Examiner, Rapporteur, and member of the PhD thesis committee of 10 PhD Theses**.

Fredrik Brännström – Curriculum Vitae

1 Higher Education Qualifications

- Dec. 2000: **Lic.Eng. in Communication Theory**, Department of Computer Engineering, Chalmers University of Technology, Gothenburg, Sweden. Thesis title: "Trellis code multiple access (TCMA) – detectors and capacity considerations."
- April 1998: **M.Sc. in Electrical Engineering**, Luleå University of Technology, Luleå, Sweden. Thesis title: "Performance analysis of LMMSE-based channel estimator for wireless OFDM and importance sampling."

2 Doctoral Degree

- April 2004: **Ph.D. in Communication Theory**, Department of Computer Engineering, Chalmers University of Technology, Gothenburg, Sweden. Dissertation title: "Convergence analysis and design of multiple concatenated codes." Supervisor: Prof. Lars K. Rasmussen.

3 Postdoctoral Positions

- May 2004 – May 2006: **Postdoc**, Communication Systems Group at the Department of Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden.
- Aug. 2005 – Nov. 2005: **Visiting Researcher**, Institute for Telecommunications Research (ITR), University of South Australia, Adelaide, South Australia, Australia.

4 Qualifications Required for Appointment as a Docent

- Nov. 2012: **Docent in Communication Systems**, Chalmers University of Technology.

5 Current Position

- Nov. 2013 – present: **Associate Professor**, Communication Systems Group at the Department of Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden. 80% time devoted to research.

6 Previous Positions and Periods of Appointment

- Sept. 2010 – Oct. 2013: **Assistant Professor**, Communication Systems Group at the Department of Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden.
- Sept. 2010 – July 2011: **Consultant**, Quantenna Communications, Inc., Fremont, CA, USA.
- June 2006 – July 2010: **Principal Design Engineer**, Quantenna Communications, Inc., Fremont, CA, USA.
- Sept. 1998 – April 2004: **Ph.D. student**, Department of Computer Engineering, Chalmers University of Technology, Gothenburg, Sweden.
- Sept. – Nov. 2001, Aug. – Sept. 2002, Feb. – June 2003: **Visiting Researcher**, Institute for Telecommunications Research (ITR), University of South Australia, Adelaide, South Australia, Australia.

7 Interruption in Research

- June 2006 – July 2010: **50 months with zero Academic research** while working as Principal Design Engineer, Quantenna Communications, Inc., Fremont, CA, USA. The research in the papers published in this period was conducted before June 2006.

8 Supervision of PhD Students

- May 2011 – present: **Mikhail Ivanov**, Lic.Eng. Dec. 2013, (main supervisor)
  Topic: "Coding, Modulation, and Coded Random Access"
- Oct. 2012 – present: **Keerthi Nagalapur**, (main supervisor)
  Topic: "MIMO Signal Processing for Vehicular Communication"
- March 2011 – present: **Wanlu Sun**, Lic.Eng. Dec. 2013, (co-supervisor)
  Topic: "Clock Synchronization and Resource Allocation for D2D Communication"
- Sept. 2011 – present: **Christian Häger**, Lic.Eng. May 2014, (co-supervisor)
  Topic: "Coding, Modulation, and Optical Communications"
- Dec. 2012 – present: **Erik M. Steinmetz**, (co-supervisor since Feb. 2015)
  Topic: "Benchmarking and Metrology of Heterogeneous Cooperative Navigation."
- Sept. 2014 – present: **Khoa Quang Huynh**, (co-supervisor)
  Topic: "Sparse-Graph Codes for Distributed Storage."
- Sept. 2014 – present: **Anver Hisham Siddique**, (co-supervisor)
  Topic: "Device to Device Communication with Vehicular Applications in 5G."

9 Research Grants

- 2015: **Basic research funding from Chalmers Area of Advance Transport**, personal grant, Amount: **350 kSEK**, (main applicant).
- 2012 – 2015: **Swedish Research Council – Project Research Grant for Junior Researcher**, Title: "MIMO-BICM: Fundamentals, Analysis, and Design," VR no. 2011-5950, personal grant, Amount: **3 280 kSEK**, (main applicant).
- 2014: **Basic research funding from Chalmers Area of Advance Transport**, personal grant, Amount: **200 kSEK**, (main applicant).
- 2007 – 2010: **Swedish Research Council – Project Research Grant for Assistant Professor**, Title: "Efficient Iterative Processing for Wireless Communication Systems," VR no. 2006-4872, personal grant, Amount: **4 156 kSEK**, (main applicant).
- 2014 – 2017: **Swedish Governmental Agency for Innovation Systems (VINNOVA), FFI – Strategic Vehicle Research and Innovation**, Title: "5G for Vehicular Applications," No. 2014-01387, Chalmers part: **4 000 kSEK** of 5 500 kSEK, (co-applicant).
- 2015 – 2016: **Swedish Governmental Agency for Innovation Systems (VINNOVA), Chalmers Antenna Systems Excellence Center (Chase), stage 4**, Title: "Antenna Systems for V2X Communication," Chalmers part: **1 300 kSEK** of 2 500 kSEK, (co-applicant).

10 Awards

- 2014: **Department of Signals and Systems' Best Teacher Award**, In 2012, the Department of Signals and Systems (S2) established an award for teachers, as a commendation for considerable educational achievements. The award is given away every second year.
- 2013: **Best Poster Award** for the poster: A. Alvarado, F. Brännström, E. Agrell, and T. Koch, "On the asymptotic optimality of Gray codes for BICM and one-dimensional constellations," presented at *IEEE Communications Theory Workshop 2013 (CTW '13)*, Phuket, Thailand, June 2013.
- 2003: "The National Information and Communications Technology Australia (NICTA) **Prize for Excellence in Postgraduate Research**" for the poster: F. Brännström, L. K. Rasmussen, and A. Grant, "Optimal scheduling for iterative decoding of multiple concatenated codes," presented at *Australian Communications Theory Workshop 2003 (AusCTW '03)*, Melbourne, Australia, Feb. 2003.

11 Committees

- 2016: **General Co-Chair**, IEEE European School of Information Theory, Gothenburg, Sweden, April 2016.
- 2015: **Local Arrangements Chair**, International Conference on Localization and GNSS, Gothenburg, Sweden,
- 2013: **General Co-Chair**, Swedish Communication Technologies Workshop (Swe-CTW 2013), Gothenburg, Sweden, Aug. 2013.
- 2012: **Organizing Committee Member**, 2012 International Symposium on Turbo Codes & Iterative Information Processing, Gothenburg, Sweden, Sept. 2012..
- 2011: **TPC Vice-Chair**, IEEE Swedish Communication Technologies Workshop (Swe-CTW 2011), Stockholm, Sweden, Oct. 2011.
- **TPC Member**: IEEE International Conference on Communications (2013, 2015), Wireless Communications and Networking Conference (2014), and IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (2012).
- **Reviewer** of many theses (B.Sc., M.Sc., and Ph.D.), journal, and conference papers.

12 Further Information

- **Scholarships and Travel Grants**: **Ericsson Research Foundation** (2001, 2002, 2013), **Alice och Lars Erik Landahls stipendiefond** (2001, 2002, 2013), **Knut och Alice Wallenbergs Stiftelse** (2005), **Wenner-Gren Foundation** (2005), **IEEE Travel Grant** (2001, 2003, 2004, 2005), **Chalmerska forskningsfonden** (2003), **Chalmers, Bidrag ur programmet Forskarstuderandes längre utlandsvistelser** (2003), **Chalmers, Bidrag ur anslaget Forskarstuderandes resor** (2001, 2002), and **Stiftelsen ISS'90** (1999).
- **Invited Talks 2012–**: Seminar at KTH **Royal Institute of Technology**, Stockholm, Sweden, (Feb. 2015), Guest lecture in the course EQ2460, KTH **Royal Institute of Technology**, Stockholm, Sweden, (Feb. 2015), Workshop on **Information Theory and Applications** (ITA), La Jolla, CA, (Feb. 2015), Workshop on **Information Theory and Applications** (ITA), San Diego, CA, (Feb. 2014), **Lund University**, Lund, Sweden, (Mar. 2013), KTH **Royal Institute of Technology**, Stockholm, Sweden, (Mar. 2013), **Linköping University**, Linköping, Sweden, (Nov. 2012), and **Cambridge University**, Cambridge, UK, (Feb. 2012).

Publication list

Alexandre Graell i Amat – Publication List 2007 – present

Citation data is based on Google Scholar database information. The five most significant publications for this project are marked with a star (★).

1 Five Most Cited Publications

[1] D. Vogrig, A. Gerosa, A. Neviani, A. Graell i Amat, S. Benedetto, G. Montorsi, "A 0.35μm CMOS analog turbo decoder for the 40-bit, rate-$1/3$, UMTS channel code," *IEEE Journal of Solid-State Circuits*, vol. 40, no. 3, pp. 753–762, March 2005.
Number of citations: 52

[2] (★)A. Graell i Amat, G. Montorsi, F. Vatta, "Analysis and Design of Rate-Compatible Serial Concatenated Convolutional Codes," in *Proc. IEEE International Symposium on Information Theory, ISIT 2005*, pp. 607–611, September 2005.
Number of citations: 43

[3] A. Graell i Amat, C. Abdel Nour, C. Douillard, "Serially concatenated continuous phase modulation for satellite communications," *IEEE Transactions on Wireless Communications*, vol. 8, no. 6, pp. 3260–3269, June 2009.
Number of citations: 39

[4] A. Graell i Amat, G. Montorsi, S. Benedetto, "Design and decoding of optimal high-rate convolutional codes," *IEEE Transactions on Information Theory*, vol. 50, no. 5, pp. 867–881, May 2004.
Number of citations: 37

[5] A. Graell i Amat, C. Abdel Nour, C. Douillard, "Serially concatenated continuous phase modulation for satellite communications," *IEEE Transactions on Wireless Communications*, vol. 8, no. 6, pp. 3260–3269, June 2009.
Number of citations: 32

2 Peer-reviewed Journal Papers

[6] R. Krishnan, G. Colavolpe, A. Graell i Amat, T. Eriksson, "Linear Massive MIMO Precoders in the Presence of Phase Noise – A Large-Scale Analysis", *IEEE Transactions on Signal Processing*, to appear.
Number of citations: 0

[7] C. Häger, A. Graell i Amat, F. Brännström, A. Alvarado, E. Agrell, "Terminated and Tailbiting Spatially-Coupled Codes with Optimized Bit Mappings for Spectrally Efficient Fiber-Optical Systems," *IEEE/OSA Journal of Lightwave Technology*, vol. 33, no. 7, pp. 1275–1285, April 2015. **Invited paper.**
Number of citations: 0

[8] M. Ivanov, F. Brännström, A. Graell i Amat, P. Popovski, "Error Floor Analysis of Coded Slotted ALOHA over Packet Erasure Channels", *IEEE Communications Letters*, vol. 19, no. 3, pp. 419–422, March 2015.
Number of citations: 1

[9] N. Bitouzé, A. Graell i Amat, E. Rosnes, "Using Short Synchronous WOM Codes to Make WOM Codes Decodable", *IEEE Transactions on Communications*, vol. 62, no. 7, pp. 2156–2169, July 2014.
Number of citations: 1

[10] E. Rosnes, M. Helmling, A. Graell i Amat, "Minimum Pseudoweight Analysis of 3-Dimensional Turbo Codes", *IEEE Transactions on Communications*, vol. 62, no. 7, pp. 2170–2182, July 2014.
Number of citations: 0

[11] C. Häger, A. Graell i Amat, F. Brännström, A. Alvarado, E. Agrell, "Improving Soft FEC Performance for Higher-Order Modulations Via Optimized Bit Channel Mappings", *Optics Express*, vol. 22, no. 12, pp. 14544–14558, June 2014.
Number of citations: 5

[12] A. Önder Isikman, H. Mehrpouyan, A. A. Nasir, A. Graell i Amat, R. A. Kennedy, "Joint phase noise estimation and data detection in coded multi-input-multi-output systems," *IET Communications*, vol. 8, no. 7, pp. 981–989, May 2014.
Number of citations: 2

[13] (★)S. Schwandter, A. Graell i Amat, G. Matz, "Spatially-Coupled LDPC Codes for Decode-and-Forward Relaying of Two Correlated Sources over the BEC," *IEEE Transactions on Communications*, vol. 62, no. 4, pp. 1324–1337, April 2014.
Number of citations: 0

[14] C. Häger, L. Beygi, E. Agrell, P. Johannisson, M. Karlsson, and A. Graell i Amat, "A Low-Complexity Detector for Memoryless Polarization-Multiplexed Fiber-Optical Channels," *IEEE Communications Letters*, vol. 18, no. 2, pp. 368–371, February 2014.
Number of citations: 0

[15] B. Makki, A. Graell i Amat, T. Eriksson, "On Noisy ARQ in Block-fading Channels," *IEEE Transactions on Vehicular Technology*, vol. 63, no.2, pp. 731–746, February 2014.
Number of citations: 5

[16] B. Makki, A. Graell i Amat, T. Eriksson, "Green Communication via Power-optimized HARQ Protocols," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 1, pp. 161–177, January 2014.
Number of citations: 8

[17] R. Krishnan, A. Graell i Amat, T. Eriksson, G. Colavolpe, "Constellation Optimization in the Presence of Strong Phase Noise", *IEEE Transactions on Communications*, vol. 61, no. 12, pp. 5056–5066, December 2013.
Number of citations: 2

[18] C. Häger, A. Graell i Amat, A. Alvarado, E. Agrell, "Design of APSK Constellations for Coherent Optical Channels with Nonlinear Phase Noise," *IEEE Transactions on Communications*, vol. 61, no. 8, pp. 3362–3373, August 2013.
Number of citations: 8

[19] A. Alvarado, A. Graell i Amat, F. Brännström, E. Agrell, "On Optimal TCM Encoders", *IEEE Transactions on Communications*, vol. 61, no. 6, pp. 2178–2189, June 2013.
Number of citations: 3

[20] A. Piemontese, A. Graell i Amat, G. Colavolpe, "Frequency Packing and Multiuser Detection for CPMs: How to Improve the Spectral Efficiency of DVB-RCS2 Systems", *IEEE Wireless Communications Letters*, vol. 2, no. 1, pp. 74–77, February 2013.
Number of citations: 4

[21] B. Makki, A. Graell i Amat, T. Eriksson, "On ARQ-based Fast-Fading Channels", *IEEE Communications Letters*, vol. 16, no. 12, pp. 1921–1924, December 2012.
Number of citations: 10

[22] B. Makki, A. Graell i Amat, T. Eriksson, "HARQ feedback in spectrum sharing networks," *IEEE Communications Letters*, vol. 16, no. 9, pp 1337–1340, September 2012.
Number of citations: 10

[23] C. Koller, A. Graell i Amat, J. Kliewer, F. Vatta, K. S. Zigangirov, D. J. Costello, Jr., "Analysis and Design of Tuned Turbo Codes," *IEEE Transactions on Information Theory*, vol. 58, no. 7, pp. 4796–4813, July 2012.
Number of citations: 7

[24] E. Rosnes and A. Graell i Amat, "Performance Analysis of 3-D Turbo Codes," *IEEE Transactions on Information Theory*, vol. 57, no. 6, pp. 3707–3720, June 2011.
Number of citations: 4

[25] A. Graell i Amat, L. K. Rasmussen, and F. Brännström, "Unifying analysis and design of generalized rate-compatible serially concatenated codes," *IEEE Transactions on Communications*, vol. 59, no. 2, pp. 343–351, February 2011.
Number of citations: 3

[26] R. Youssef and A. Graell i Amat, "Distributed serially concatenated codes for multi-source cooperative relay networks," *IEEE Transactions on Wireless Communications*, vol 10., no. 1, pp. 253–263, January 2011.
Number of citations: 32

[27] N. Bitouzé, A. Graell i Amat, E. Rosnes, "Error correcting coding for a non-symmetric ternary channel," *IEEE Transactions on Information Theory*, vol. 56, no. 11, pp. 5715–5729, November 2010.
Number of citations: 1

[28] A. Graell i Amat, R. Le Bidan, "Minimum distance and convergence analysis of Hamming-accumulate-accumulate codes," *IEEE Transactions on Communications*, vol. 57, no. 12, pp. 3518–3523, December 2009.
Number of citations: 1

[29] C. Berrou, A. Graell i Amat, Y. Ould Cheikh Mouhamedou, Y. Saouter, "Improving the distance properties of turbo codes using a third component code: 3D turbo codes," *IEEE Transactions on Communications*, vol. 57, no. 9, pp. 2505–2509, September 2009.
Number of citations: 27

[30] A. Graell i Amat, E. Rosnes, "Good concatenated code ensembles for the binary erasure channel," *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 6, pp. 928–943, August 2009.
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Fredrik Brännström – Publication List 2007 – present

Citation data is based on Google Scholar database information. The five most significant publications for this project are marked with a star (★).

Interruption in research: June 2006 – July 2010 (50 months with zero Academic research) while working as Principal Design Engineer, Quantenna Communications, Inc., Fremont, CA, USA. The research in the papers published in this period was conducted before June 2006.

1 Five Most Cited Publications

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Dissertation title (en)
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Dissertation title (en)		
Convergence Analysis and Design of Multiple Concatenated Codes		
Organisation	**Unit**	**Supervisor**
Chalmers tekniska högskola, Sweden Sweden - Higher education Institutes	Department of Computer Engineering	Lars K. Rasmussen
Subject doctors degree	**ISSN/ISBN-number**	**Date doctoral exam**
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Publications

Name: Alexandre Graell i Amat	**Doctorial degree:** 2004-12-06
Birthdate: 19760128	**Academic title:** Docent
Gender: Male	**Employer:** Chalmers tekniska högskola

Graell i Amat, Alexandre has not added any publications to the application.

Publications

Name: Fredrik Brännström	**Doctorial degree:** 2004-04-12
Birthdate: 19740408	**Academic title:** Docent
Gender: Male	**Employer:** Chalmers tekniska högskola

Brännström, Fredrik 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.