Application

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Descriptive data

Project info

Project title (Swedish)*

Hårdvarubegränsad kod design för trådlös transmission med låg fördröjning och hög tillförlitlighet

Project title (English)*

Code design for low-latency high-reliability wireless transmission with implementation constraints

Abstract (English)*

The revolutionary development in microelectronics has led to inexpensive yet powerful devices that can communicate, sense, and act on their environment. Such devices and the networks they form bring together communication, computation, sensing and control, enabling new applications at an unprecedented scale. Such machine-type communication (MTC) is expected to have a substantial impact throughout society. Contrasted against the current 2-4G wireless systems MTC systems impose entirely different constraints due to specialised applications and specific implementation. This concerns in particular stronger requirements on latency, reliability and implementation complexity. In view of these challenges the purpose of the research program is to develop a comprehensive code design framework for low-latency high-reliability wireless transmission with implementation constraints. The aims of the research program are to: 1) Establish relevant tradeoffs relating reliability, latency, and implementation complexity; 2) Develop an analytical code-design framework for low-latency high-reliability wireless transmission with implementation constraints.

Popular scientific description (Swedish)*

Sedan mitten av 90-talet har vi sett en närmast explosionsartad användning av trådlösa kommunikationssystem. Den trådlösa kommunikationstekniken står nu inför ett generationsskifte där den tidigare motivationen att förbinda människor kompletteras av en önskan att designa trådlösa kommunikationssystem för kommunikation mellan maskiner. Den drivande faktorn bakom dessa maskin-till-maskin-system är delvis vidareutvecklingen av automatiserade system inom den traditionella processindustrin, där övergången från trådbunden till trådlös kommunikation leder till förenklingar och kostnadsminskningar. Andra tillämpningar är fjärrstyrd övervakning, men också till exempel automatiserade säkerhetssystem för koordination av fordonsnätverk, där trådbunden kommunikation av förklarliga skäl är utesluten. Ett annat växande tillämpningsområde är kommunikation i så kallade sensornätverk, med tillämpningar inom till exempel miljöforskningen.

De nya kommunikationssystemen ställer nya krav. Ett trådlöst trafiksäkerhetssystem ställer till exempel betydligt högre krav på pålitlighet och maximal fördröjning än ett system designat för mediadistribution. Ett system för övervakning av miljön i ett geografiskt område kan till exempel ställa höga krav på energieffektivitet för att kunna vara verksamt under långa perioder utan underhåll, och kan även ställa krav på låg beräkningskomplexitet i varje kommunikationslänk för att minska kraven på processorer och elektronik och därmed bli mer ekonomiskt hållbart. Den underliggande teorin för design och analys av kommunikationssystem och nätverk har dock mestadels utvecklats med mer traditionella kommunikationstillämpningar i åtanke, och kan därför ofta inte tillgodose dessa nya krav på ett fundamentalt plan utan endast genom kostnadskrävande efterkonstruktioner.

För att möta de krav som morgondagens kommunikationstillämpningar kommer att ställa, vill vi därför vidareutveckla den underliggande och grundläggande kommunikationsteorin för maskin-till-maskin-tillämpningar. Vi föreslår ett forskningsprogram där vi tittar på en kombinerad design. De implementationsbegräsningar som avses innefattar stringenta krav på maximal fördröjning, samt begränsningar på den mängd beräkningar som tillåts.

Forskningen kommer att bedrivas i en av Sveriges starkaste forskningsmiljöer inom området; på Kungliga Tekniska Högskolan (KTH) i Stockholm. Resultaten av forskningen förväntas bli teorier och lösningar av fundamental karaktär, som sedan kan tillämpas i utvecklingen av morgondagens system för maskin-till-maskin-kommunikation.

Project period

Number of project years*

3

Calculated project time*

2016-01-01 - 2018-12-31

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

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

Keyword 1*

Error control coding

Keyword 2*

Low latency

Keyword 3*

High reliability

Keyword 4

Implementation constraints

Keyword 5

Rate adaptive

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*

Nothing to report

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

A1 PURPOSE AND AIMS

The revolutionary development in microelectronics has led to inexpensive yet powerful devices that can communicate, sense, and act on their environment. Such devices, and the networks they form, bring together communication, computation, sensing and control, enabling new applications at an unprecedented scale. Such machine-type communication (MTC) is expected to have a substantial impact throughout society. Contrasted against the current 2-4G wireless systems that were primarily designed for human-type communication and wireless Internet-access, MTC systems impose entirely different constraints due to specialised applications and specific implementation. This concerns in particular stronger requirements on latency, reliability and implementation complexity, as opposed to the strong focus on bandwidth efficiency in current systems. In view of these challenges the purpose of the proposed research program is to develop a comprehensive design framework for *low-latency high-reliability wireless transmission with implementation constraints*.

As the main tool for improving reliability we consider error-control coding schemes operating in the physical layer. The use of multiple antenna systems is also relevant, but not explicitly targeted in this proposal. Considering physical-layer parameters, as well as relevant link-layer queueing parameters, latency depends primarily on transmitter/receiver processing, propagation delay, and queueing delay, which are connected to implementation complexity, block length, and queue arrival/service rates; in turn, reliability and implementation complexity depend primarily on channel quality, transmission rate, and block length. We therefore propose to: 1) explore recent results on achievable transmission rates under assumptions of finite block length, channel quality, and reliability; 2) consider processing delays and energy requirements due to VLSI implementation complexity; and 3) investigate joint optimisation of queueing and channel-adaptive transmission. It follows that to reach our purpose, the aims of the proposal are to:

1. Establish relevant tradeoffs relating reliability, latency, and implementation complexity;
2. Develop an analytical code-design framework for low-latency high-reliability wireless transmission with implementation constraints.

A2 SURVEY OF THE FIELD

Fundamental Limits of Finite Block-Length Error-Control Coding

The Shannon capacity [1] has since 1948 been the fundamental design tradeoff for reliable transmission, characterising the maximum achievable transmission rate as a function of bandwidth and power. As the block length grows large, the probability of block error goes to zero. The reliability/latency tradeoff is neglected in Shannon's formulation, and has only recently been appropriately determined by Polyanskiy *et al.* [2]. Here achievable rates are characterised as a function of the Shannon capacity, block length, block error probability, and channel dispersion. Explicit bounds and approximations are derived for the binary erasure channel (BEC), the binary symmetric channel (BSC), and the additive white Gaussian noise (AWGN) channel. Not surprisingly a certain back-off[1] from the Shannon capacity is required for transmission with a given finite block length and target reliability.

The proposed tradeoffs enable new potential design approaches for practical error-control codes that directly take the fundamental relationship between bandwidth, power, latency, and reliability into consideration.

In further work, Yang *et al.* have investigated the finite-block-length behaviour for fading channels. In [3] the finite block length tradeoff is derived for quasi-static fading channels with multiple antennas. Here, each codeword is transmitted over one fading block characterised by a random channel coefficient and AWGN. Therefore there is a non-zero probability that a channel realisation cannot support the current rate. Such channels are characterised by the outage capacity, defined as

[1] The back-off for an AWGN channel is determined as $\sqrt{V/n} \cdot Q^{-1}(\epsilon) + \mathcal{O}(\log n/n)$, where V is the channel dispersion, n is the block length, ϵ is the block error probability, and $\mathcal{O}(\log n/n)$ is a vanishing second order term.

the maximum achievable rate under the assumption of a non-zero block error probability ϵ. It is shown that the channel dispersion is zero, regardless of whether channel state information (CSI) is available at the transmitter and/or the receiver. It therefore follows that the first-order back-off term is zero, and thus there is a fast convergence towards the outage capacity as the block length increases. For block lengths between 500 and 1000 symbols it is demonstrated that the codes used in LTE-Advanced achieve about 85% of the maximum coding rate.

Analytical code design for block-fading channels are notoriously complicated; however, as the dispersion has been shown to be zero, existing methods code design strategies may be sufficient.

In block-fading channels, the use of power control can significantly increase the maximal rate. Exploiting CSI at the transmitter and the receiver, different power levels can be allocated to different blocks, thus maximising the overall rate. With a short-term power constraint, the maximum power in each block is limited, while for a long-term power constraint the average power over all codewords and channel realisations is limited [4, 5]. The optimal solution for capacity-achieving codes was presented in [4, 5], and known as water-filling. However, truncated channel inversion is an attractive practical alternative. Here a channel-quality threshold is determined, and if a channel realisation is above the threshold power allocation will equalise the channel. For channel realisations below the threshold, transmission is turned off. This problem has now been revisited for finite block length in [6], where it is shown that truncated channel inversion is both first-order and second-order optimal. Furthermore, the solution is appealing from an implementation point-of-view, as it follows current practise.

We will seek to extend our prior work on code design for power controlled block-fading channels to the case of finite-block-length codes [7].

Complexity Measures based on Models of VLSI Implementation

Different approaches have been investigated for quantifying the VLSI implementation complexity of a decoding strategy into a tractable measure. A particular suitable circuit model was proposed by Thomson in [8], consisting of a set of axioms that defines a VLSI circuit and a computation. The *energy complexity* of a VLSI circuit implementation realising an algorithm is then defined as the area of the circuit multiplied by the number of clock cycles required to execute the algorithm.

The influence of encoder/decoder complexity has been treated in an information-theoretic context in [9–11]. Thomson's model is here applied to link processing power to relevant code parameters given a target block error rate. For short-range communications the decoding processing power is comparable to transmit power, and can therefore not be ignored in the transmission power budget. A fundamental trade-off is derived, showing that the transmit power must be strictly larger than the Shannon limit in order to keep the total power consumption small. Considering transmission over an AWGN, and optimising over transmit power, a lower bound on the total power scaling is $\Omega(\sqrt[3]{\log(1/P_e^{\text{blk}})})$, where P_e^{blk} is the block error probability[2]

Closely related problems are considered by [12, 13] in a graph-theoretic context. Here, consider a code of block length n and rate R transmitted over a BEC with erasure probability ϵ. A key result in [12] is a lower bound on the required processing energy per bit for parallel decoding of any coding scheme, relating the code parameters, and the channel erasure probability: $E_{\text{dec}} > K_{\text{tech}}\sqrt{(\log_2 n)/(\log_2(\epsilon^{-1}))} = \Omega(\sqrt{\log(1/(1-R/C))})$.[3] The consequences of this result are that both the total energy of a decoding algorithm and the energy per bit must approach infinity as capacity is approached[4]. Thus, if the total decoder energy per bit is to be optimised, a rate strictly less than capacity must be used.

To optimise the decoder energy per bit, what is the optimal rate?

[2]The notation $\Omega(\sqrt[3]{\log(1/P_e^{\text{blk}})})$ signifies that the total power scales with P_e^{blk} as $\sqrt[3]{\log(1/P_e^{\text{blk}})}$.

[3]Here E_{dec} is the average decoder energy, and K_{tech} is a constant that depends on circuit technology parameters.

[4]The minimum block length scales as $n \approx \gamma/(1-R/C)^2$, where γ is a constant and C is capacity [14].

Another key result in [12] is a fundamental lower bound on the energy complexity scaling for a fully parallel decoding algorithm, $\Omega(n\sqrt{\log n})$. However, in [13] it is shown that the energy complexity of a parallel decoding scheme that directly implements the corresponding Tanner graph of any LDPC code must have an energy complexity that scales as $\Omega(n(\log n)^2)$. It is not yet known whether or not the fundamental bound is tight; nor is it known yet whether the implementation of an LDPC code based directly on the Tanner graph cannot be energy-complexity optimal. However, these observations open up interesting new problems of implementation-constrained coding theory and practical techniques.

A motivated starting point is to investigate new LDPC code structures with a better energy complexity profile that may approach the fundamental lower bound on scaling.

Error-Control Code-Design Strategies
Emerging applications will, in addition to traditional resources and performance constraints, place specific emphasis on delay and complexity. Such concerns have been somewhat neglected by the coding community since the era of modern coding theory. The invention of Turbo codes [15] and the rediscovery of low-density parity-check (LDPC) block codes [14, 16, 17] simply redirected the attention towards optimal capacity-achieving coding schemes for point-to-point links [18–20]. Existing code-design frameworks for turbo codes [15] and low-density parity-check (LDPC) block codes [14] are based on asymptotic performance analysis techniques, where a single performance measure is tracked over decoding iterations. Popular frameworks are based on density evolution (DE) [14, 19] or extrinsic information transfer (EXIT) charts [20–22]. For transmission over a BEC, DE typically tracks the decoder extrinsic erasure rate, and an EXIT chart tracks the mutual information of the decoder extrinsic erasure rate. These frameworks assume an infinite block length, and hence are useful for streaming and applications that require large blocks. Extensions to accommodate complexity constraints also exist, e.g., [23–26]; in each of these design approaches, a complexity cost is assigned to certain decoding features, e.g., number of iterations, activation schedule, bit-representation. An optimisation problem is then formulated to obtain a complexity-constrained solution.

It will be useful to integrate relevant VLSI-model parameters for energy complexity into a new implementation-constrained design framework.

For finite block lengths, scaling laws have been proposed inspired by related problems in statistical physics [27]. Here the finite-length performance is found as a scaled version of the corresponding infinite block-length performance. Combinatorial techniques have also been proposed [28], however, due to exponentially growing complexity, they are typically only applicable to relatively short codes. Modifications to accommodate finite block length within the existing design frameworks have also been considered. However, for a finite block length the random distortions of the channel cannot be considered ergodic, and thus the ensemble concentration towards the mean behaviour is not perfect. In [29] the distribution of the extrinsic mutual information, given a certain a-priori mutual information, is obtained numerically and approximated by a normal distribution to estimate the block error rate using EXIT charts. A similar approach is used in [30]; however here a band of EXIT curves, containing 99% of the ensemble, is used for the code design by EXIT charts. This strategy is akin to the more general approach based on information combining developed in [31].

It is clear that a comprehensive theoretical framework for the design of finite block length coding schemes, achieving optimal trade-offs between reliability, latency and complexity, is needed.

Delay-Constrained Transmission
In the design of wireless networks, Quality of Service (QoS) guarantees for delay-constrained applications, such as data rate, delay, and delay-violation probability, have typically been provided by the analysis of corresponding queuing systems at the link layer. In [32] a pure queuing model is considered where the effect of channel variations on link performance is captured by a single

function termed the *effective capacity*; an idea that has recently been extended to the finite block length regime in [33], where the fundamental results in [2] have been explored. The focus in [32] is on the queuing model, with the assumption of capacity-achieving channel codes applied at the physical layer. To capture a useful cross-layer scenario a joint queueing and coding model was proposed in [34]. In this cross-layer setting the link-layer QoS depends on both delay violations due to link-layer buffer overflow, and on decoding errors introduced by the finite block length channel code. It follows that an optimal joint queueing and coding approach must balance these two possible error events in an optimal way. Fundamental results were derived based on effective capacity and random coding bounds for rate-adaptive transmission of finite block length codes over a block-fading channel. The use of practical finite block length rate-compatible low-density parity-check (LDPC) block codes and LDPC convolutional codes within the rate-adaptive strategy was termed queued-codes and investigated numerically in [35, 36]. However, no explicit design frameworks were developed for the rate-adaptive transmission or for the specific codes applied in the examples.

Here a promising direction for code design is the use of the capacity-achieving rate-compatible LDPC convolutional code families proposed in [37], suitably modified for finite block length, and trade-offs between reliability, latency and complexity.

In [38] a new strategy for finite block length rate-adaptive transmission over a block-fading channel is proposed by the applicant *et al.* as an improvement to queued-codes. Here CSI is causally available (only CSI up to and including the current block is available) at both the transmitter and the receiver. For the infinite block length case the optimal power allocation strategy for power-adaptive systems with causal CSIT is characterised in [39] using a dynamic programming approach; in the infinite block-length regime the optimal rate-adaptive strategy is straightforward: block-wise transmission at a rate equal to the instantaneous capacity. For the more realistic finite-block-length case, rate adaptation is not as trivial. In this scenario, there exists a trade-off between transmission rate/throughput, block length and error probability [3]. Rate adaptation requires a coding scheme whose code rate can be adapted causally across the fading blocks. One such attempt is introduced in [40]; however, no attempt was made to find the optimal rate-adaptation strategy. In [38] a sequential coding scheme is suggested for causal rate adaptation, which generalizes the code with expandable message space introduced in [40]. Similar to [39] a dynamic programming approach is applied to optimise the system throughput, subject to an average block error probability constraint. Numerical results show that the proposed adaptation rule provides significant gains compared to non-adaptive transmission and the trivial block-wise adaptive transmission scheme. Furthermore, the performance of the suboptimal scheme is close to the upper-bound benchmark achieved by systems with full CSIT.

This scheme is, so far, a theoretical approach. A practical rate-compatible streaming coding scheme is required to provide a strong alternative to existing queued-codes.

Recently, spatially coupled (SC) LDPC codes [41], have received great attention, as they provide a universal way of achieving capacity with efficient iterative decoding techniques. As the block length grows large, the performance of the suboptimal belief propagation (BP) decoding algorithm tends to the Shannon limit [42]. Thus, such codes are attractive for applications that require large block lengths and for streaming. Streaming codes play a vital role in delay-sensitive networked control applications of unstable processes, where they are essential for optimal control over noisy channels. The concept of anytime communications proposed in [43] allows for the receiver to decide when to commence decoding, thus being in control of the latency. Here, the reliability is required to improve exponentially with the latency incurred until decoding is initiated. SC-LDPC codes are well-suited to meet these requirements, and the first anytime SC-LDPC codes were proposed in [44], co-authored by the applicant. Indeed, similar to convolutional codes, these codes can operate either as block codes (when appropriately terminated) or as streaming codes with corresponding sliding-window encoding and decoding. A sliding-window decoder was proposed in [45], providing efficient streaming capabilities with good tradeoffs between decoding latency and error rate. Moreover the decoding latency can be set and changed on-the-fly as required; thus a particular block in the streaming code can meet strict delay constraints, while still benefiting from decoding over a full window of such blocks. This is a useful characteristic for adaptively accommodating varying requirements of reliability and latency on-the-fly.

Controlling MTC-type systems via wireless links and wireless networks is paramount for the success of many applications. It is therefore important to develop relevant coding schemes with strict latency and reliability constraints for operation over wireless links.

A3 PROJECT DESCRIPTION

In this project we focus on the design of error-control coding schemes for low-latency high reliability transmission with implementation constraints. As block length is a main contributor to latency, we are in particular interested in the analysis and design of finite-block-length codes, and how they compare to the fundamental bounds of Polyanskiy *et al.* in [2]. Further sources of latency is queueing delay (at link layer) and decoding errors (at physical layer), both leading to potential delay violation. With the wide range of potential applications in MCT, it is imperative to also bring in aspects of VLSI implementation, both in terms of measures of complexity and processing delay, directly into the analytical design framework. To focus our investigation we have organised the project into three interrelated research tracks.

Track 1 is dedicated to the development of analysis and design tools for finite-block-length coding schemes with implementation constraints. Here we will mainly focus on graph-based codes. The biggest challenge of the project is to deduce a useful design approach from the moderate-deviation theory, characterising the non-asymptotic regime. Our initial plan is to revisit the theoretical foundation of extrinsic information transfer (EXIT) charts in [22] with a focus on the non-asymptotic regime. Another challenge is to integrate relevant parameters from the analysis of energy complexity for VLSI circuits into a comprehensive implementation-constrained design framework.

In Track 2 we leverage recent fundamental information-theoretic [9, 10] and graph-theoretic [12, 13] bounds on complexity in terms of decoder processing power in a VLSI implementation, how it scales with block length, and how it relates to the total transceiver power consumption. As both communities conclude that it is not possible to communicate at the Shannon capacity rate with bounded processing power, it seems vital to integrate measures of processing power into design frameworks.

A cross-layer approach is taken in Track 3, where we consider a joint design of queueing and rate-adaptive transmissions with strict latency constraints. The foundation is a new rate-adaptive transmission strategy co-developed by the applicant, as a more powerful alternative to queued-codes proposed in [34–36]. Here our initial plan is to first construct more advanced queued-codes based on the capacity-achieving rate-compatible codes in [37], and then subsequently consider the design of finite-block-length codes with implementation constraints. We will also investigate finite-length anytime codes for extensions to queued-codes.

The research team consists of two new Ph.D. students (A and B) (80% commitment) to be recruited, and the main applicant (30% commitment) as the project leader. For the period (M1-M18)[5] the focus for both students will be on Track 1, developing the basis for a finite-block-length code design framework. From M12 student A will be assigned to Track 2, and student B to Track 3, while still contributing relevant extensions to the low-latency high-reliability code design frameworks with implementation constraints.

More details of the research problems addressed in the three research tracks are found below.

[5] Month 1 to Month 18 of the project.

Track 1: Latency, Reliability and Implementation Constraints (M1-M18)

A significant challenge of this track is to develop an analytical code design framework for finite-block-length codes. This is an entirely new direction of research that has not previously been explored, and thus have a great potential for new fundamental insights. For simplicity we will initially consider transmission over a BEC, and subsequently extend our scope to other channel models. Our starting point is the elegant approach in [22], where the EXIT-charts approach is brought onto a solid theoretical foundation. In particular, the gap-to-capacity of codes of infinite block length is characterised for transmission over a BEC, by the *area theorem*. With a convenient decoder model the gap is found as the area between the two curves in the EXIT chart, and thus capacity-achieving codes need the two curves to be perfectly matched. It follows that the code design problem is converted to a curve-fitting problem. Ironically finite-length codes need to be designed with at least the gap-to-capacity determined in [2]. It is, however, not obvious how to relate the results in [2] with the results in [22], or how to incorporate the results in [2] into existing design frameworks. As many different parameters have been used for tracking the performance evolution over the iterative decoding process of modern codes, we will look for alternative measures to track, which will allow us to revisit the decoder model in [22]. In particular, we will investigate the information-theoretic concepts explored in [2], e.g., information density and channel dispersion, as they playing important roles in the non-asymptotic regime. Our aim is to provide a theoretically justified design framework for finite-length graph codes, and to design finite-length codes that achieve the bounds in [2].

As a heuristic alternative, we will investigate the use of EXIT charts, suitably modified to account for finite block length as in [29, 30]. The finite-length performance over a given stochastic channel is subject to variations, since a finite-length channel realisation is not ergodic. We therefore have a distribution of EXIT curves for each component decoder. Considering transmission of a length n codeword over a BEC with erasure probability δ, the number of erasures in an arbitrary channel realisation is binomial distributed as $B(n, \delta)$. It is therefore possible to analytically determine the respective distributions of EXIT curves, rather than conducting numerical evaluation as done in [29, 30] where an AWGN channel is considered. To design a code of length n with a decoder block erasure probability ϵ for transmission over a BEC with erasure probability δ the rate should have a certain gap to capacity, according to the finite-block-length trade-off [2]. It follows that the problem is no longer a curve-fitting problem, as for the asymptotic case, but rather an *area-fitting* problem, due to the required gap-to-capacity between the two EXIT curves.

Track 2: Energy-Complexity Optimal LDPC Codes (M13-M36)

The task in Track 2 is to investigate new LDPC code structures with improved energy complexity scaling profile as compared to the scaling profile $\Omega(n^2)$ of existing LDPC codes. In particular, we are looking for energy-complexity optimal codes, meeting the lower scaling bound $\Omega(n\sqrt{\log n})$ derived in [13], but still providing competitive decoding thresholds and error floor performance. Creating a sequence of LDPC codes that avoids the poor scaling law $\Omega(n^2)$ with probability greater than 0 may be possible, as suggested in [13]. For example, by changing the random generation rule for the LDPC graph the variable nodes and check nodes can be placed uniformly scattered through a grid on the VLSI circuit area. The random placement of edges can then be chosen uniformly over a choice of local edges connecting variable and check nodes that are close to each other, rather than uniformly over all possible edges. Here we can apply our experience from designing anytime LDPC convolutional codes for networked control applications [44]. For anytime codes, it is an important feature that reliability keeps improving with increasing latency for a particular block. At the same time recent blocks must also quickly reach a certain level of reliability. This requires a graph with locally connected variable and check nodes, complemented by a small number of check nodes with long reach. Initially we will design codes based on our anytime experience, and determine corresponding energy complexity scaling following the approach in [13], while at the same time evaluating code performance though density evolution and numerical simulations. The goal is subsequently to provide general principles and recommended structural rules for for the construction of optimal energy complexity scaling LDPC codes for integration into the design framework developed in Track 1.

Track 3: Queued Codes for Rate-Adaptive Transmission (M13-M36)

The first task in Track 3 is to design a capacity-achieving queued-code for streaming transmission over a simplified block-fading channel based on the rate-compatible LDPC convolutional code family in [37]. For the initial design and analysis, we consider a block-random BEC, defined as follows. For each new code block the channel is a BEC with a randomly selected erasure probability $\delta < 1/2$. The infinite-block-length queued-code will establish an optimal scheme to compare our subsequent finite-block-length queued-codes against. The second task is to suitably redesign the code family in [37] to accommodate implementation constraints and finite-block-length optimisation. With this framework at hand, we will progressively consider more challenging block-fading channels, arriving at a suitable design framework for Rayleigh block-fading channel with AWGN. For the Rayleigh block-fading channels, the finite-block-length design framework needs to be accommodated the corresponding finite-block-length trade-offs in [3].

With an efficient queued-code design framework available, we will adapt our finite-block-length anytime codes to the queued-code scenario. Flexible window decoding using the approach in [45] will be investigated to provide a delay-adaptive decoding process. In effect we will construct the first family of rate-compatible rate-adaptive anytime codes. Through our ongoing collaboration with the Department of Automatic Control at KTH, we will test these new anytime codes in a relevant industrial-automation simulation setup, demonstrating that unstable processes can be kept under control wirelessly with strict latency and reliability.

The rate-adaptive scheme used in the queued-codes is straightforward, and with room for improvements. A more advanced scheme is proposed in [38]. Here, based on causal CSI at the transmitter, an optimal rate-allocation can be found using a dynamic programming approach ensuring maximum throughput. The designed queued-codes can be directly applied in the new rate-adaptive strategy. Based on an information-theoretic performance evaluation, the throughput of the scheme is close to the case of having full CSI available a-causally; a result that should also be demonstrated with practical queued-codes. For comparison, we will also consider a power-adaptive strategy based on our previous work in [7].

A4 SIGNIFICANCE

Our technical focus on low-latency, high-reliability wireless transmission with implementation constraints is both timely and highly relevant in view of ongoing 5G research activities. Our expected outcomes, as detailed in each research track, represent significant technical contributions towards both theory and practical implementation. Core design frameworks emphasising latency, reliability, and implementation complexity will have significant impact across the field of wireless communications.

We expect to make significant pioneering contributions in this area of low-latency high-reliability wireless transmission, especially in terms of connecting practical implementation constraints with theoretical design frameworks for error-control coding. The area has a strong potential for significant breakthroughs with clear industrial and academic impact. Our results will be disseminated via papers in high-quality international (IEEE) conferences and journals. Besides published research results, the main outcome of the project will be the graduation of two Ph.D students in the area of low-latency high-reliability wireless transmission; we emphasise the importance of providing the Stockholm area with well-qualified researchers in this field. The process industry, the heavy vehicle industry, and the wireless systems industry are prime users of wireless networks with strict delay and reliability constraints. It is therefore of significance that capabilities in this area is being build up and passed on to graduating Ph.D.s that can take these strategies into the relevant industries for practical use.

A5 PRELIMINARY RESULTS

Relevant to Track 1, we have developed two related code design frameworks for sparse graph codes with complexity constraints [LR31, LR40][6], as well as a design framework for rate-compatible turbo codes [LR25]. The experience from these frameworks will accelerate the development of the design frameworks proposed here. In addition we have developed a finite-length analysis approach for anytime SC-LDPC codes, based on a combinatoric approach, that provides remarkable good agreement with simulation results [LR3]. For short block lengths this approach will provide an alternative direction of analysis. Relevant for Track 3, the rate-adaptive transmission strategy investigated has been proposed by the applicant and co-authors. In addition, we have developed an optimal power control scheme for LPDC codes in block-fading channels [LR20], which we will use to provide a benchmark for our rate-adaptive scheme.

A6 INTERNATIONAL AND NATIONAL COLLABORATION

The Department of Communication Theory at KTH has formal and informal contacts with many leading institutions worldwide. The main collaborative contacts of the applicant are listed below. The strong position of the group in the European research community is manifested by participation in a wide range of EU-funded networks and projects. Examples of completed projects are: ACE-II, NEWCOM, SENDORA,WINNER, WINNER II, Acropolis, AMIMOS, FEEDNETBACK, QUASAR. The applicant is coordinating a Marie Currie IRSES project TEASCONE with TU Munich, University of Cambridge, and University of South Australia as partners. On the national arena, the department participates in the ACCESS Linnaeus Center.

The main applicant has a long history of cooperation and exchange. The most notable instances are summarized below (sv = PhD student visit[s]; rv = (post PhD) research visit[s]; jpp = joint paper[s], published/accepted; jps = joint paper[s], submitted).

Institution (name of main contact[s])	Type	Institution (name of main contact[s])	Type
Princeton (Verdú)	rv, jpp	Northwestern Univ. (Guo)	jpp
Uni Toronto (Kschischang)	rv	UniSA (Grant, Nguyen, Chan, Lechner)	sv, rv, jpp
UNSW (Yuan)	sv, rv, jpp	CSIRO (Collings)	jpp
NUS (Lim)	rv,jpp	I^2R (Sun, Tan)	rv, jps
NTU (Guan, Chong)	rv	City Uni HK (Li Ping)	rv
Supelec (Debah)	jpp	UPF (Guillén i Fàbregas)	sv, rv, jpp
TUM (Timo, Kramer)	rv, jps	Cambridge (Sayir)	rv
Aalto (Vehkaperä, Wickman)	jpp	Aalborg (Fleury)	rv, jpp
Chalmers (Brännström, Graell i Amat)	rv, jpp	LiU (Björnson)	jpp

A7 OTHER GRANTS

The purpose of my ongoing project entitled “Variable-length coding with feedback” is to develop analysis and design tools for variable-length coding schemes with feedback that accurately capture the effects of finite block-lengths. The purpose of the proposed project is to develop a comprehensive design framework for low-latency high-reliability wireless transmission with implementation constraints. Both projects are motivated by recent new fundamental bounds on the maximum rate of finite block length codes. However, *Variable-length coding with feedback* and *finite-block-length coding* are two related, but quite different topic areas within the fields of coding theory and code design. I therefore see no significant overlap between the two projects.

[6]Citations are made to the publication list of the applicant.

References

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[3] Wei Yang, G. Durisi, T. Koch, and Y. Polyanskiy, "Quasi-static multiple-antenna fading channels at finite blocklength," *IEEE Trans. Inf. Theory*, July 2014.

[4] A. J. Goldsmith and P. P. Varaiya, "Capacity of fading channels with channel side information," *IEEE Trans. Inf. Theory*, Nov. 1997.

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[23] F. Brännström, L. K. Rasmussen, and A. J. Grant, "Convergence analysis and optimal scheduling for multiple concatenated codes," *IEEE Trans. Inf. Theory*, Sept. 2005.

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[26] I. Hussain, I. Land, T. Chan, M. Xiao, and L. K. Rasmussen, "A new design framework for LT codes over noisy channels," in *IEEE ISIT*, 2014.

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[45] A. R. Iyengar, M. Papaleo, P. Siegel, and J. K. Wolf, "Windowed decoding of protograph-based LDPC convolutional codes over erasure channels," *IEEE Trans. Inf. Theory*, Apr. 2012.

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

Project Title: Variable-length coding with feedback

File number: 2012-34415-97171-15

Dnr: 2012-4061

Funding: 2 730 000 SEK

Period: 2013-2015

The Ph.D. student Iqbal Hussain has been working on the project since the start in 2013. He defended successfully his dissertation on the 17th of December 2014. Ph.D. student Leefke Grosjean has been working on the project since January 2014. She is expected to defend her dissertation by the end of 2015.

Scientific Results:

Iqbal has been working exclusively on rateless codes with a single possitive feedback, which is Track 1 in the project plan. His scientific results are reported in publications listed below. His main contributions have been to:

1. Develop a comprehensive design framework for unequal error protection for rateless coding;
2. Develop several design approaches for complexity-constrained rateless coding;
3. Design a new strategy for selecting variable nodes to ensure the best possible error floor performance;
4. Develop a comprehensive design framework for buffer-based distributed rateless coding, providing high reliability.

Leefke has been working exclusively on anytime LDPC convolutional codes with feedback, which is Track 2 in the project plan. She has had one journal paper published. This is a pioneering paper, proposing the first anytime code based on modern coding theory. She has made important contributions to the design and analysis of anytime LDPC convolutional codes; especially a finite-length performance analysis based on a combinatoric approach is a novel contribution thta allows for an accurate estimate of error rate performance.

Publications:

I. Hussain, M. Xiao, and L. K. Rasmussen, "Generalized unequal erasure protection for buffer-based distributed LT codes," *IEEE Trans. Commun.*, submitted Dec. 2014, revised March 2015.

Grosjean, L. K. Rasmussen, R. Thobaben, and M. Skoglund, "Systematic LDPC convolutional codes: Asymptotic and finite-length anytime properties," *IEEE Trans. Commun.*, vol. 62, no. 12, pp. 4165–4183, Dec. 2014.

I. Hussain, M. Xiao, and L. K. Rasmussen, "Buffer-based distributed LT codes," *IEEE Trans. Commun.*, vol. 62, no. 11, pp. 3725-3739, Nov.

I. Hussain, I. Land, T. Chan, M. Xiao, and L. K. Rasmussen, "New Design Framework for LT Codes over Noisy Channels," *IEEE Int. Symp. Inf. Theory* (Honolulu, USA), July 2014.

I. Hussain, M. Xiao, and L. K. Rasmussen, "Rateless codes for the multi-way relay channel," *IEEE Wireless Commun. Letters*, vol. 3, pp. 457-460, May 2014.

I. Hussain, M. Xiao, and L. K. Rasmussen, "Reduced-complexity decoding of LT codes over noisy channels," *IEEE Wireless Commun. Networks Conf.* (Shanghai, China), April 2013.

I. Hussain, M. Xiao, and L. K. Rasmussen, "Design of LT codes with equal and unequal erasure protection over binary erasure channels," *IEEE Commun. Letters*, vol. 17, pp. 261-264, Feb. 2013.

I. Hussain, M. Xiao, and L. K. Rasmussen, "Regularized variable-node LT codes with improved erasure floor performance," *Inf. Theory and Appl. Workshop* (San Diego, USA), Feb. 2013.

Relationship Between Approved Project and Envisaged Project:

The purpose of my ongoing project entitled "Variable-length coding with feedback" is to develop analysis and design tools for variable-length coding schemes with feedback that accurately capture the effects of finite block-lengths. The purpose of the proposed project is to develop a comprehensive design framework for low-latency high-reliability wireless transmission with implementation constraints. Both projects are motivated by recently developed fundamental bounds on the maximum rate of finite block length codes. "Variable-length coding with feedback" and "low-latency, high reliability finite-length coding with delay and implementation constraints" are two related, but quite different topic areas within the fields of coding theory and code design. I therefore see no significant overlap between the two projects.

Accumulated Research Resources

The VR funding has been able to almost support two Ph.D. students at 80% activity level for two years, at a cost of roughly 750 kkr per student per year. Iqbal Hussain was active 80% in the project 2013-2014, and Leefke Grosjean has been active 80% in 2014 and will be active 80% in 2015. The shortfall of 270 kkr, as well as the remaining 20% of funding for both students has been funded by the KTH faculty funds for research, research education. My 20% involvement in the project has been funded by VR via the ACCESS Linnaeus Center.

VR project funds 2013-2015: 2730 kkr

KTH faculty funds for research, research education: 2013-2015: 645 kkr

VR via the ACCESS Linnaeus Center: 2013-2015: 760 kkr
Total: 4135 kkr.

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	Lars Kildehøj	30
2	Other personnel without doctoral degree	TBD	80
3	Other personnel without doctoral degree	TBD	80

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	Total
1	Applicant	Lars Kildehøj	10	133,100	137,100	141,200	411,400
2	PhD Student	TBD	80	423,300	472,400	491,200	1,386,900
3	PhD Student	TBD	80	423,300	472,400	491,200	1,386,900
	Total			979,700	1,081,900	1,123,600	3,185,200

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	Total
1	Office space	119,000	131,000	136,000	386,000
	Total	119,000	131,000	136,000	386,000

Running Costs

	Running Cost	Description	2016	2017	2018	Total
1	Travel		20,000	60,000	60,000	140,000
2	Publication costs			15,000	15,000	30,000
	Total		20,000	75,000	75,000	170,000

Depreciation costs

Depreciation cost	Description	2016	2017	2018

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	Total, applied	Other costs	Total cost
Salaries including social fees	979,700	1,081,900	1,123,600	3,185,200	822,800	4,008,000
Running costs	20,000	75,000	75,000	170,000		170,000
Depreciation costs				0		0
Premises	119,000	131,000	136,000	386,000		386,000
Subtotal	1,118,700	1,287,900	1,334,600	3,741,200	822,800	4,564,000
Indirect costs	358,000	396,000	411,000	1,165,000	300,800	1,465,800
Total project cost	1,476,700	1,683,900	1,745,600	4,906,200	1,123,600	6,029,800

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

Salary Costs

Research in this project is planned for two Ph.D. student at an activity level 80% and the applicant at activity level 30%. From VR, we seek for funding of 80% of two new Ph.D. students and 10% of one Professor.

Office Space

The costs for office space are calculated at a fixed rate of 12.1% of the salary costs.

Travel Costs

The travel costs consider conference travels for the applicant and the involved PhD students. In order to make the results of the project visible, up to three travels to international high-quality IEEE conferences per year are expected (except for the first year).

Publication Costs

Publication costs include open access fees for journal publications.

Indirect Costs

Indirect costs include KTH taxes (23.6% of salary costs), school taxes (6.28% of salary costs), and department taxes (6.68% of salary costs).

Other Costs

The remaining 20% involvement in the project by the main applicant, and the remaining 20% of each of the Ph.D. students are funded by KTH faculty funds for research, and research education.

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

CV

Curriculum Vitae - Lars Kildehøj Rasmussen (1/2)

University Degrees, Post-Doc Position, Docent, Present and Prior Positions

B.1 Civ. Ing. 1989, Electrical Engineering, Danmarks Tekniske Højskole.

B.2 Ph.D. 1993, Electrical Engineering, Georgia Institute of Technology (USA), Trellis Coded Adaptive Rate Hybrid-ARQ Protocols over AWGN and Slowly Fading Rician Channels, Prof. Stephen B. Wicker.

B.3 Post-Doc 93-95, Institute for Telecom Research, University of South Australia.

B.4 Docent 2000, Chalmers University of Technology.

B.5 Professor, Dept. Communication Theory, KTH Royal Institute of Technology, 50%.

B.6 2002-08, Professor, Institute for Telecom. Research, University of South Australia.
1999-02, Associate Professor, Dep. Comp. Eng., Chalmers University of Technology.
1998-99, Visiting Professor, Dep. Electrical Engineering, Univ. of Pretoria, South Africa.
1995-98, Senior Researcher, Centre for Wireless Communications, NUS, Singapore.

B.7 None.

B.8 Ph.D. Students and Postdoctoral Fellows

Graduated Ph.D. Students:
Maksym Girnyk (2014)
Iqbal Hussain (2014)
Robert Milner (2010)
Khoa D. Nguyen (2009)
Peng Hui Tan (2005)
Elisabeth Uhlemann (2004)
Fredrik Brännström (2004)
Paul K. Gray (1999)
Paul D. Alexander (1997)
Lei Wei (1994)

Postdoctoral Fellows:
Mikko Vehkapeä (2011-2013)
Vishwambhar Rahti (2010-2011)
Gottfried Lechner (2008-2010)
Ingmar Land (2007-2009)
Yi Hong (2005-2007)
Peng Hui Tan (2005)
Fredrik Brännström (2005)
Albert Guillén i Fàbregas (2004-2006)
He Ping (1996-1998)
Teng Joon Lim (1995-1996)

Current Ph.D. Students:
Ahmed Zaki
Leefke Grosjean

Current Ph.D. Students:
Nan Li
Peter Larsson

Selected Research Grants 2005-2012

2013-15 "Variable-Length Coding with Feedback," Swedish Research Council, PI

2013-15 "Enabling Technologies for Large-Scale Sensor and Control Networks (TEASCONE)," FP7 Marie Curie IRSES Programme, PI

2012-14 "Physical Layer Security Techniques for Multiuser Wireless Networks," Australian Research Council, CI.

2010-12 "Coding for Wireless Transmission with Limited Feedback and Imperfect Channel State Information," Swedish Research Council, PI.

2009-11 "Efficient Transmission Strategies for Cooperative Wireless Ad Hoc Networks," Australian Research Council, PI.

2007-09 "Adaptive Broadband Wireless Communication," Australian Research Council, PI.

2006-08 "Complexity Constrained Iterative Information Processing," Australian Research Council, PI

2005-07 "Quality-of-Service-Based Adaptive Coding for Wireless Communications Networks,"Australian Research Council, PI.

2003-05 "Communication System Design Using an Iterative Processing Paradigm," Swedish Research Council, PI.

2003-05 "Iterative Architectures for Data Communications," Australian Research Council, PI.

Curriculum Vitae - Lars Kildehøj Rasmussen (2/2)

Publications

Citation data is based on ISI / Scopus / Google Scholar data bases.

Journal Papers:	59	Book Chapters:	5
Conference Papers:	167	Patents:	3
Total citations:	974 / 1419 / 3440		

IEEE Editorial Responsibilities

Since 2013	Associate Editor, IEEE Transactions on Wireless Communications.
2002-2013	Associate Editor, IEEE Transactions on Communications.
2008	Guest Editor, IEEE Journal on Selected Areas in Communications, Special Issue on *"Multiuser Detection for Advanced Communication Systems and Networks."*

Assessment for Funding Bodies

2015	International Reviewer, Hong Kong Research Council.
2013	International Reviewer, Danish Research Council for Independent Research.
2012	Communication Engineering Panel, Academy of Finland.
2008-present	International Expert Assessor, Australian Research Council.
2005-08	Australian-based Expert Assessor, Australian Research Council.

Selected Technical Program Committees

2012	Co-chair, PHY Track, IEEE Int. Symp. Personal, Indoor, Mobile Radio Comms.
2010	Co-chair, PHY-Layer Track, IEEE Wireless Communications Networks Conf.
2009	Co-chair, Comms Theory Symposium, IEEE Global Conf. on Communications.
2010	TPC member, Int. Symposium on Turbo Codes & Iterative Information Processing.
2005-15	TPC member, IEEE International Conference on Communications.
2005-15	TPC member, IEEE Int. Symp. on Personal, Indoor, and Mobile Radio Comms.
2003-15	TPC member, IEEE Vehicular Technology Conference.
1999-15	TPC member, IEEE Global Communications Conference.

Involvement in Research Degree Examination

Opponent:	7 Ph.D. defences (Canada, Denmark, Finland, France, Hong Kong, Portugal).
Committees:	17 Ph.D. Examination committees.

Professional Duties

2011-2014	Member of the IEEE Information Theory Society Conference Committee.
2011-present	Vice-Chair (ITSoc), IEEE Sweden Joint VT-COM-IT Chapter.
2009-present	Member of the IEEE Sweden Joint VT-COM-IT Chapter Board.

Further Information

2012	General Co-chair, 7th International Symposium on Turbo Codes and Iterative Information Processing, Gothenburg.
2011	General Chair and Founder, IEEE Swedish Communications Technology Workshop (Swe-CTW), Stockholm.
2004-08	Network Convenor, ARC Communications Research Network (ACoRN) Australian research network of excellence in the area of telecommunications.
2002	Co-founder of Cohda Wireless Pty Ltd (http://www.cohdawireless.com/) A leading developer of Safe Vehicle and Connected Vehicle design solutions.
1998	Outstanding Researcher' Award, National University of Singapore.

Publication list

Publication List 2007 – 2015 – Lars Kildehøj Rasmussen

Citation data is based on Google Scholar Citations. A full list of publications is found at: https://dl.dropboxusercontent.com/u/9783638/Rasmussen-March-2015.pdf

Five Most Cited Publications

[1] P. H. Tan and L. K. Rasmussen, "The application of semidefinite programming for detection in CDMA," *IEEE J. Sel. Areas Commun.*, vol. 19, pp. 1442–1449, Aug. 2001.
Number of citations: 179.

[2] L. K. Rasmussen, T. J. Lim, and A.-L. Johansson, "A matrix-algebraic approach to successive interference cancellation in CDMA," *IEEE Trans. Commun.*, vol. 48, pp. 145–151, Jan. 2000.
Number of citations: 155.

[3] D. Guo, L. K. Rasmussen, S. Sun, and T. J. Lim, "A matrix-algebraic approach to linear parallel interference cancellation in CDMA," *IEEE Trans. Commun.*, vol. 48, pp. 152–161, Jan. 2000.
Number of citations: 155.

[4] F. N. Brännström, L. K. Rasmussen and A. J. Grant, "Convergence analysis and optimal scheduling for multiple concatenated codes," *IEEE Trans. Inf. Theory*, vol. 51, no. 9, pp. 3354–3364, Sept. 2005.
Number of citations: 144.

[5] L. Wei, L. K. Rasmussen, and R. Wyrwas, "Near optimum tree-search detection schemes for bit-synchronous multiuser CDMA systems over Gaussian and two-path Rayleigh fading channels," *IEEE Trans. Commun.*, vol. 45, pp. 691–700, June 1997.
Number of citations: 120.

Refereed Journal Papers

[LR1] M. A. Girnyk, A Müller, M. Vehkaperä, L. K. Rasmussen, and M. Debah "On the asymptotic sum rate of downlink cellular systems with random user locations," *IEEE Wireless Commun. Letters*, accepted for publication.
Number of citations: 0.

[LR2] M. Vehkaperä, T. Riihonen, M. A. Girnyk, E. Björnson, M. Debbah, L. K. Rasmussen, and R. Wichman, "Asymptotic analysis of MIMO channels with transmitter noise and mismatched decoding," *IEEE Trans. Commun.*, vol. 63, no. 3, pp. 749–765, March 2015.
Number of citations: 2.

[LR3] (★)L. Grosjean, L. K. Rasmussen, R. Thobaben, and M. Skoglund, "Systematic LDPC convolutional codes: Asymptotic and finite-length anytime properties," *IEEE Trans. Commun.*, vol. 62, no. 12, pp. 4165–4183, Dec. 2014.
Number of citations: 1.

[LR4] I. Hussain, M. Xiao, and L. K. Rasmussen, "Buffer-based distributed LT codes," *IEEE Trans. Commun.*, vol. 62, no. 11, pp. 3725–3739, Nov. 2014.
Number of citations: 1.

[LR5] P. Larsson, L. K. Rasmussen, and M. Skoglund, "Throughput analysis of hybrid ARQ in Gaussian block-fading channels," *IEEE Trans. Commun.*, vol. 62, no. 7, pp. 2569–2588, July 2014.
Number of citations: 4.

[LR6] N. Schrammar, M. Skoglund, C. Wang, and L. K. Rasmussen, "New achievable rates for Gaussian partially cognitive interference channels with multiple cognitive pairs," *IEEE Trans. Commun.*, vol. 62, no. 6, pp. 2051–2060, June 2014.
Number of citations: 0.

[LR7] I. Hussain, M. Xiao, and L. K. Rasmussen, “Rateless codes for the multi-way relay channel,” *IEEE Wireless Commun. Letters*, vol. 3, pp. 457–460, May 2014.
Number of citations: 1.

[LR8] S. Chatterjee, D. Koslicki, S. Dong, N. Innocenti, L. Cheng, Y. Lan, M. Vehkaperä, M. Skoglund, L. K. Rasmussen, E. Aurell, and J. Corander, “SEK: Sparsity exploiting k-mer-based estimation of bacterial community composition,” *Bioinformatics*, vol. 30, no. 17, pp. 2423–2431, April 2014.
Number of citations: 4.

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Research education

Dissertation title (swe)
Trellis Coded, Adaptive Rate Hybrid-ARQ Protocols over AWGN and Slowly Fading Rician Channels

Dissertation title (en)
Trellis Coded, Adaptive Rate Hybrid-ARQ Protocols over AWGN Channels and Slowly Fading Rician Channels

Organisation	Unit	Supervisor
Georgia Institute of Technology, USA Not Sweden - Higher Education institutes	School of Electrical and Computer Engineering	Stephen B. Wicker

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
20203. Kommunikationssystem		1993-08-10

Publications

Name: Lars Kildehøj	**Doctorial degree:** 1993-08-10
Birthdate: 19650308	**Academic title:** Professor
Gender: Male	**Employer:** Kungliga Tekniska högskolan

Kildehøj, Lars 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.