Application

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Descriptive data

Project info

Project title (Swedish)*

Trådlösa accessmetoder för kritisk kommunikation med låga fördröjningar i dynamiska nät

Project title (English)*

Wireless Medium Access for Critical Low-Latency Communication in Highly Dynamic Networks

Abstract (English)*

Communication that requires that the information is delivered with very high probability within a certain deadline is referred to as critical communication. A system where nodes move in and out of the communication range unpredictably is called a highly dynamic network. The main objective of this project is to analyze a promising class of medium access protocol, namely coded slotted ALOHA (CSA). It is believed that CSA can provide reliable low-latency communication for many uncoordinated users. Here CSA is applied to cooperative vehicular communications, since that is one of the most challenging problems in communication engineering today. The reliability for such an application needs to be very high and it is also necessary that the latency is low to assure traffic safety. Our suggested approach to predict the performance and to optimize the system is based on stopping sets, borrowed from the framework for low-density parity-check (LDPC) codes. The outcomes of the project are a fundamental knowledge about CSA that can also be used in other communication systems that require reliable low-latency communication in highly dynamic networks.

Popular scientific description (Swedish)*

Kritisk kommunikation är kommunikation där det är avgörande att informationen kommer fram till mottagaren inom en viss specificerad tid för att undvika allvarliga konsekvenser som till exempel kroppsskada, förlust av liv eller ekonomisk förlust. Dynamiska nät kan definieras som system där användare kommer och går oförutsägbart. Det är en utmaning att konstruera kommunikationssystem som har hög tillförlitlighet med låg fördröjning och dessutom klarar av ett dynamiskt nät.

Fordonskommunikation, där fordonen kommunicerar direkt med varandra utan att koordineras av en basstation, har just alla de egenskaperna. Det är därför en av de största utmaningarna inom trådlös kommunikation idag. Informationen som skickas mellan fordonen måste komma fram med hög sannolikhet inom en viss tid för att säkerställa trafiksäkerheten och undvika olyckor som i värsta fall kan ha dödlig utgång.

Kodad ALOHA är en accessmetod som uppfyller kraven för kritisk kommunikation i dynamiska nät. Syftet med det här projektet är att undersöka om kodad ALOHA kan användas för att uppnå de stränga kraven som fordonskommunikation ställer. Målet är att använda verktyg för att prediktera prestandan och även optimera parametrar i systemet så att kraven uppnås. Vi tror även att kodad ALOHA kan användas i andra system som har många användare och som ställer stora krav på hög tillförlitlighet och samtidigt låg fördröjning. Resultaten från det här projektet kan därför även användas i dessa 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

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

Keyword 1*

vehicular communication

Keyword 2*

slotted ALOHA

Keyword 3*

uncoordinated multiple access

Keyword 4

codes on graphs

Keyword 5

performance analysis

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

Wireless Medium Access for Critical Low-Latency Communication in Highly Dynamic Networks

Fredrik Brännström and Alexandre Graell i Amat

1 Purpose and Aims

Critical communication applications are defined here as applications that require very high reliability, i.e., that data packets are delivered with very high probability within a certain deadline, to avoid serious consequences (bodily injury, loss of life, severe environmental impact, or great financial loss). It is challenging to simultaneously provide low latencies (end-to-end delays) and high reliability, especially over wireless networks with highly dynamic network topologies, i.e, when communication nodes move in and out of communication range quickly and unpredictably. An example of a critical service is teleprotection of the electrical power grid [1] and an example of a low-latency service is the so-called tactile Internet [2]. An important system that combines requirements of *high reliability* and *low latency* over *highly dynamic network* topologies is vehicular communication (VC) for traffic safety and efficiency applications [3].

In the future, vehicles will be capable of communicating directly with each other without help from fixed infrastructure such as base stations or access points. Messages will be sent between all vehicles to let everyone know where all surrounding vehicles are located and what their intentions are. This important knowledge can be used to avoid accidents (traffic safety) and to improve traffic flow (traffic efficiency). Reliable VCs is presently one of the most challenging problems of communication engineering, as it includes all the above-mentioned challenges: high mobility networks with rapidly changing topologies and a large number of users, poor channel quality, and strict reliability and latency requirements. The current industrial state-of-the-art systems for VC are severely suboptimal [4], and new ideas and design at both the physical (PHY) the medium access control (MAC) layers are therefore highly sought after.

The purpose of this project is to analyze a new and promising class of medium access methods, namely coded slotted ALOHA (CSA), for use in highly dynamic VC networks. To reach our aim to provide reliable low-latency VC, the specific goals of this project are to:

1. Develop tools to accurately predict the performance of VC networks with strict requirements on latency and error performance;
2. Optimize settings to maximize the efficiency and minimize the error performance;
3. Determine if more practical model assumptions will degrade the performance in comparison to ideal assumptions.

We use VC as a means to build fundamental knowledge about CSA, since we believe that VC is a very challenging application. However, the project results will be more broadly applicable, as CSA can be used for medium access in any system that require reliable, low-latency communication.

2 Survey of the Field

A crucial part of any communication system with more than one user is the chosen multiple access method. Two very common methods are frequency divison multiple access (FDMA) and time division multiple access (TDMA). FDMA is used in, e.g., terrestrial radio broadcast where the base station (BS) (in this case the radio tower) uses a dedicated frequency band for each radio station. TDMA is used in, e.g., Global System for Mobile Communications (GSM) where time is divided into eight slots to support eight different users in the same frequency band. Both these methods are examples of *coordinated* medium access protocols, where it is predetermined which frequency band to use or where a BS decides which time slots different mobile devices should use.

In VC it is important to keep the latency (the time it takes to deliver and decode the information) to a minimum. Having coordination between all vehicles would increase the latency and the communication load in the network due to all handshakes and acknowledgments (where the users agree on what resources to use). In addition, a VC network is very dynamic since vehicles have high speed and therefore the set of users that can be reached by a specific vehicle changes quickly (vehicles enter and leaves the local network without notice). Sensitivity to latency and a dynamic network make it difficult to have a coordinated channel access method for VC networks.

2.1 Vehicular Communication

The current status of VCs is summarized in the standard [5] and is usually referred to as 802.11p. The PHY and the MAC layer in 802.11p are based on the WiFi protocol that works well for low mobility high throughput networks. In the context of VCs, the PHY layer is mainly criticized for not being able to cope with time-varying channels [6]. 802.11p uses carrier sense multiple access with collision avoidance (CSMA-CA) as the medium access protocol. Shortly described as follows; in CSMA-CA a user that wants to transmit, first waits until the channel is free, then decreases a counter with a certain frequency starting from a random integer, and transmits when zero is reached. If the channel becomes busy during the countdown, the user halts the countdown until the channel is free again. CSMA-CA does not require any coordination and is shown to work well for networks with a small number of users, large amounts of information to be transmitted to each user, and no latency constraints. Under these conditions, CSMA-CA can provide large throughputs [7]. In vehicular *ad hoc* networks (VANETs), however, the number of users is large, the amount of information to be transmitted is rather small, and there are hard deadlines for accessing the channel. In such scenarios, CSMA-CA fails to provide a reliable channel access.

Other *uncoordinated* medium access protocols used in VCs can be roughly divided into two classes: i) The ones based on CSMA-CA, that try to improve its performance by adjusting the load by means of power control [8] or transmission rate control [9]. However, they retain the drawbacks of the original CSMA-CA. ii) The second class includes self-organizing protocols predominantly based on TDMA, which are advantageous for overloaded networks [10], but cannot guarantee high reliability. These self-organizing algorithms require a learning phase, which increases the channel access delay and hence the latency. Moreover, transmission errors during this learning phase make such protocols unusable.

2.2 Uncoordinated Medium Access Using ALOHA

The ALOHA System [11] was developed by the University of Hawaii in the late 60s and early 70s. It was the first wireless packet data network demonstrated for the public. In ALOHA, many nodes (or users) share the medium. However, in contrast to coordinated TDMA, the nodes are uncoordinated and allowed to transmit whenever they want. If a collision is detected (even only for part of the transmission), the involved nodes wait a random time until they retransmit the same packet. This solution later became referred to as pure ALOHA (PA). Fig. 1(a) illustrates an example of a PA system with 5 users communicating with one BS. Each user picks a random time to transmit its packet and each packet is assumed to be of equal length, T_s [seconds]. All packets that are transmitted without a collision are assumed to be decoded without error by the BS. In the example in Fig. 1(a), the packets from user 1 and 2 collide as well as the packets from user 4 and 5 (colored in red). The only packet that is received without collision is the packet from user 3 (colored in green).

Instead of letting the users randomly choose a time to transmit, a slotted frame can be introduced, i.e., slotted ALOHA (SA) [12]. Fig. 1(b) illustrates an example of an SA system with 5 users and 6 slots. At the beginning of the frame the users pick a random slot within the frame to transmit in. Comparing the PA system in Fig. 1(a) with the corresponding SA system in Fig. 1(b), it is clear that for this example 3 of the 5 users in the SA system are received without collisions, while user 1 and 2 are still in collision.

SA was later extended to diversity slotted ALOHA (DSA), where each user picked two random slots within the frame to transmit the packet and a copy of the packet [13]. This can be generalized to DSA-d, where each user transmits d replicas of its packet within the frame. DSA can be further generalized so that the users in the same system can use a different number of replicas, so called irregular repetition slotted ALOHA (IRSA), which was first introduced in [14]. IRSA can be represented by a polynomial (or distribution) $\Lambda(x) = \sum_d \Lambda_d x^d$, where Λ_d represents the fraction of users of degree d (users that transmits d replicas of their packet within the frame) such that $\Lambda(1) = 1$. SA and DSA-d are just special cases of IRSA, where the distributions are simply $\Lambda(x) = x$ and $\Lambda(x) = x^d$, respectively. Fig. 1(c) shows an example of IRSA where user 1, 2, and 5 have degree 2 and user 3 and 4 have degree 3. The instantaneous distribution in this example is therefore $\Lambda(x) = 0.6x^2 + 0.4x^3$. In Fig. 1(c), only user 4 (colored in green) can be decoded since that is the only user that has a packet without collision (in slot 3).

If each packet contains pointers to the other packets transmitted by the same user, this can be utilized

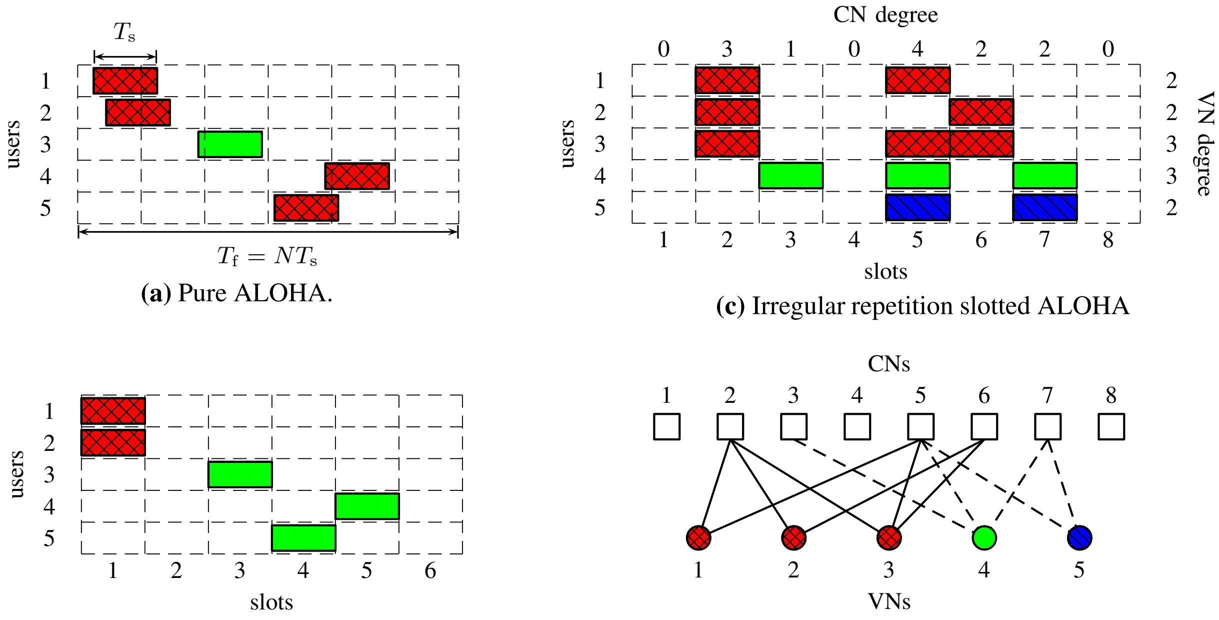


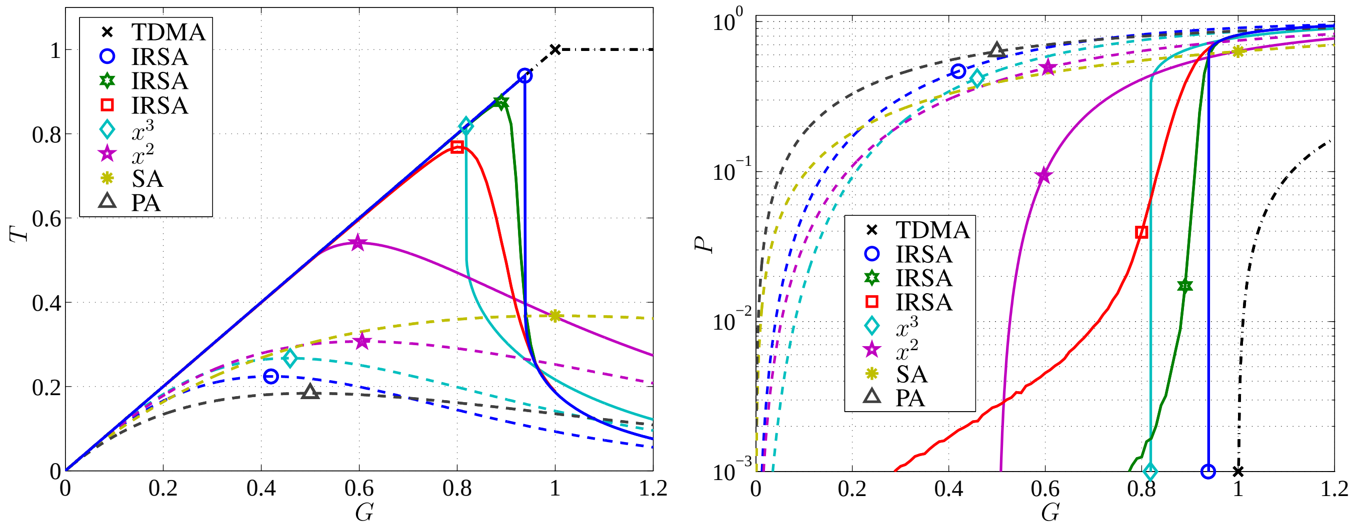
Figure 1: Different ALOHA protocols.

to improve the performance using successive interference cancellation (SIC). The BS first buffers the received signal, decodes all packets from slots without collisions, and attempts to reconstruct the packets in collision exploiting the introduced redundancy. For example, after user 4 in Fig. 1(c) is decoded in slot 3, the BS knows that this user also transmitted identical packets in slot 5 and 7. Assuming ideal SIC can be used by the BS to perfectly remove user 4's contribution in these two slots. Now it is possible to decode user 5, since after the SIC, slot 7 only contains a single packet from user 5. The SIC can continue until the residual signal in all slots (after performing SIC) contains collisions. Applying SIC to DSA is called contention resolution diversity slotted ALOHA (CRDSA) and was first suggested in [15] for DSA-2, and later extended to DSA-d in [16], here referred to as CRDSA-d.

IRSA in its most general from can be represented by a bipartite graph, where each user corresponds to a variable node (VN) and each slot to a check node (CN), which was first observed in [14]. Fig. 1(d) shows the graph representation of the example in Fig. 1(c). User 1 (or VN 1) is connected to slot 2 and 5 (or CNs 2 and 5), and so on. CNs 1, 4, and 8 are not connected to any VN, which can also be seen in Fig. 1(c). Only CN 3 has degree 1, while CNs 6 and 7 have degree 2, CN 2 has degree 3, and CN 5 has degree 4, which is evident by the number of edges connected to these CNs. The SIC can also be visualized on this graph. First all VNs that are connected to CNs of degree 1 are removed, and all the edges connected to these VNs. These are the users that are decoded in schemes without SIC (e.g., SA, DSA-d, and IRSA without SIC), illustrated by the green VN in Fig. 1(d) and the green user in Fig. 1(c). The successive iterations are then following the same procedure, i.e., remove all VNs that are connected to CNs of degree 1 and all their corresponding edges, until there are no more CNs of degree 1. After removing VN 4 (and its edges), VN 5 is connected to CN 7 that now has degree 1 and therefore VN 5 and its edges are removed (colored in blue in Fig. 1(d)). After VNs 4 and 5 (and their dashed marked edges) have been removed, the three remaining VNs are all connected to CNs that have degree 2 or higher (colored by red in Fig. 1(c) and Fig. 1(d)). Since all slots have now collisions with two or more packets, the iterations stop and the remaining users are declared unresolved. As will be evident later, these unresolved users will result in an error floor in the performance and therefore be referred to as *stopping sets* [17].

2.3 Performance Analysis of ALOHA

Let M denote the number of users and N the number of slots in a frame. Assuming that the slot duration has the same length as the packets, the frame duration is $T_\mathrm{f} = NT_\mathrm{s}$ as indicated in Fig. 1(a). To compare different systems, the *throughput* T is defined as the probability of successful packet transmission per slot, $T \triangleq R/N$, where R is the number of resolved (or correctly decoded) users. In addition, the *channel load*



(a) Throughput vs. channel load

(b) PLR vs. channel load

Figure 2: Dashed curves are without SIC and solid curves are with SIC (see legend in Table 1).

Table 1: Legend to Fig. 2, ordered in decreasing $T^\star$.

	$\Lambda(x)$	N	i	$T^\star$	$@G$	$G^\star$
-×-TDMA	–	$T_\mathrm{f}/T_\mathrm{s}$	0	1.00	≥ 1.0	1.0
-○-IRSA	$\Lambda^\star(x)$	∞	∞	0.94	0.94	0.94
-✡-IRSA	$\Lambda^\star(x)$	2000	∞	0.87	0.89	–
-◇-CRDSA-3	x^3	∞	∞	0.82	0.82	0.82
-□-IRSA	$\Lambda^\star(x)$	200	∞	0.77	0.80	–
-★-CRDSA-2	x^2	∞	∞	0.54	0.60	0.50
-✱-SA	x	∞	0	0.37	1.00	0.00
-★-DSA-2	x^2	∞	0	0.31	0.61	–
-◇-DSA-3	x^3	∞	0	0.27	0.46	–
-○-IRSA	$\Lambda^\star(x)$	∞	0	0.22	0.42	–
-△-PA	x	$T_\mathrm{f}/T_\mathrm{s}$	0	0.18	0.50	–

is defined as the number of users per slot $G \triangleq M/N$. In a coordinated TDMA system, the BS assigns a separate slot for each user. For simplicity assume that user j transmits in slot j. In such a system there are no collisions as long as $M \leq N$. Since there are no collisions $R = M$ and $T = G$ as long as $G \leq 1.0$. For channel loads larger than one, there are no more available slots and the throughput stays at 1.0.

For PA, the throughput can be expressed in closed form as $T = G\,\mathrm{e}^{-2G}$ [11]. The maximum throughput $T^\star = 1/(2\,\mathrm{e}) \approx 0.184$ is achieved for $G = 0.5$. For SA the throughput has a similar form $T = G\,\mathrm{e}^{-G}$ that achieves a maximum that is twice as high as for PA, $T^\star = 1/\,\mathrm{e} \approx 0.368$ at $G = 1.0$ [12]. In other words, just by introducing slots in the frame, the maximum throughput is doubled and for a channel load twice as high. In Fig. 2(a), the throughput for PA as a function of channel load is plotted with a dashed black curve, where $T^\star$ is indicated by a triangle. The throughput for SA and its maximum value are also shown in Fig. 2(a) by the yellow dashed curve and the star, respectively. As a reference, the throughput for coordinated TDMA is indicated by a black dashed-dotted curve.

Assuming that the frame length tends to infinity, $N \to \infty$, density evolution (DE) can be used to predict the asymptotic performance [18]. For IRSA this is described in detail in [14]. The average *packet loss rate* (PLR) is defined as the fraction of unresolved users $P \triangleq \frac{M-R}{M}$. The probability that an edge in the graph is unknown after i iterations using SIC is described by the recursive formula $p_i = 1-\mathrm{e}^{-G\Lambda'(p_{i-1})}$, where $p_{-1} = 1$ and $\Lambda'(x) = \sum_d d\Lambda_d x^{d-1}$ is the derivative of $\Lambda(x)$ with respect to x. The average PLR after i iterations can now be expressed as $P_i = \Lambda(p_i)$ [14]. If no SIC is used, $p_0 = 1 - \mathrm{e}^{-G\Lambda'(1)}$ where $\Lambda'(1) = \sum_d d\Lambda_d$. If SIC is used, the performance predicted by DE, $P = \Lambda(p)$, uses the p that fulfills $p = 1 - \mathrm{e}^{-G\Lambda'(p)}$, which is easiest found by using the recursive formula and letting $i \to \infty$. To simplify notaion, the index i is from now on dropped from the expressions. Using the definitions of G, T, and P, the throughput is related to the PLR through $T = G(1-P)$, where P is either calculated using DE for $N \to \infty$ (as explained above) or simulated for finite N.

For DSA-d, the analytical expression for the PLR and the throughput are $P = (1-\mathrm{e}^{-dG})^d$ and $T = G(1-(1-\mathrm{e}^{-dG})^d)$, which coincide with SA for $d = 1$, i.e., $P = 1-\mathrm{e}^{-G}$ and $T = G\,\mathrm{e}^{-G}$. DE can be used to predict the performance for CRDSA-d and for any distribution in IRSA with SIC in general, when $N \to \infty$. DE can also be used to optimize distributions in IRSA. It has been shown that the soliton distribution, $\Lambda_{\mathrm{S}}(x) \triangleq \sum_{d=2}^{N} \frac{d}{d(d-1)} x^d$, is an optimal distribution, i.e., the throughput goes arbitrarily close to 1.0 [19]. However, the optimality only occurs when the number of terms in the distribution (which is equal to the number of slots) goes to infinity. In [14], differential evolution was used to search over distributions with finite number of terms that maximize the throughput, or similarly, maximize the channel load $G^\star$ when the PLR suddenly drops to zero (sometimes referred to as the threshold). If the maximum degree of the distribution is set to 8, the optimal distribution is $\Lambda^\star(x) \triangleq 0.50x^2 + 0.28x^3 + 0.22x^8$ with $T^\star = G^\star = 0.94$ [14].

Fig. 2(a) shows the calculated throughput for PA, SA, DSA-2, DSA-3, and IRSA with $\Lambda^\star(x)$ without SIC, as dashed curves. The same figure also includes some of the schemes using SIC, namely CRDSA-2, CRDSA-3, and IRSA with $\Lambda^\star(x)$. Their corresponding maximum throughputs $T^\star$ are also marked and tabulated in Table 1 (in decreasing order of $T^\star$) together with the threshold $G^\star$ (if applicable). The increase in throughput by using SIC is remarkable. The maximum throughput increases from $T^\star = 0.31$ for DSA-2 to $T^\star = 0.54$ for CRDSA-2 (74%), from $T^\star = 0.27$ for DSA-3 to $T^\star = 0.82$ for CRDSA-3 (over 200%), and from $T^\star = 0.22$ for $\Lambda^\star(x)$ without SIC to $T^\star = 0.94$ for $\Lambda^\star(x)$ with SIC (327%).

Fig. 2(b) shows the corresponding PLR, where the markers represent the point when the throughput is at its maximum. Comparing Fig. 2(a) and Fig. 2(b), it is clear that maximizing the throughput is not the same as minimizing the PLR. The only simulated curves in these two figures are the red and the green curves using $\Lambda^\star(x)$ with $N = 200$ and $N = 2000$, marked with a square and a hexagram, respectively. These two curves should be compared to the blue solid curve (marked with a circle) predicted by DE for $N = \infty$. From this it is evident that for finite N, the performance in terms of T and P is far from the performance predicted by DE. It is also clear that the PLR will suffer from an error floor for finite N.

Recently an even more general scheme than IRSA has been proposed called CSA [20, 21]. In CSA the users are not necessarily repeating the packets as in IRSA, but instead using a more powerful code to add redundancy. The information is first divided into k segments and then encoded into $n > k$ segments before n mini-slots of duration T_{s}/k are picked at random for transmission [21]. IRSA is then just a special case of CSA, where $k = 1$ and $n = d$ for the different users. A more powerful code than the repetition code preserves transmission energy by lowering the amount of redundant data transmitted from each user. From now on, CSA is used to refer to all kinds of different SA schemes, where CRDSA and IRSA are just special cases of CSA.

2.4 All-to-all Broadcast Coded Slotted ALOHA

There are two types of packets in VCs, namely decentralized environmental notification messages (DENMs) and cooperative awareness messages (CAMs). DENM packets are event driven and requested by a higher-layer application, e.g., in case of an emergency. On the other hand, CAM packets are status updates (or heartbeats) and sent periodically, e.g., 10 times per second, and include information about the vehicle's position, speed, heading, etc. [22]. Consider a scenario where vehicles in the network periodically broadcast CAMs to all neighboring vehicles. Unlike classical CSA, where a BS is the intended recipient of the messages, every user acts as a BS. We propose to use CSA for this scenario, which we call all-to-all broadcast CSA (B-CSA) [23]. Each user is equipped with a half-duplex transceiver, i.e., a user cannot receive packets in the slots it uses for transmission, which is the main difference of B-CSA with respect to the classical unicast CSA discussed in Section 2.2.

As explained in Section 2.2, the instantaneous distribution for the example in Fig. 1(c) is $\Lambda(x) = 0.6x^2 + 0.4x^3$, observed by the BS that can listen to all 8 slots. If the same example is used as a B-CSA system, the distribution will be different. For example, since user 1 transmits in slots 2 and 5, it cannot receive during these slots. Therefore, from user 1's point of view it seems like there are only 4 users (and not 5), where users 2, 3, and 5 have degree 1, and user 4 has degree 2 (since slot 2 and 5 are not available). The distribution observed by user 1, the *induced* distribution, is therefore $\Lambda^{(1)}(x) = 0.75x + 0.25x^2$. The induced distributions observed by the remaining users are: $\Lambda^{(2)}(x) = 0.50x + 0.25x^2 + 0.25x^3$, $\Lambda^{(3)}(x) = 0.50 + 0.25x + 0.25x^2$, $\Lambda^{(4)}(x) = 0.25 + 0.25x + 0.50x^2$, and $\Lambda^{(5)}(x) = 0.50x + 0.50x^2$. One direct observation is that for B-CSA there are always users of degree 1 and even degree 0. Users with degree 0 can never be decoded, since their packets are not received and therefore they are always in error.

In our preliminary work [23] we show how to derive the induced distributions in B-CSA starting with any arbitrary distribution (see also Section 5).

It is possible to show that all induced distributions are equal to the original distribution, $\Lambda^{(k)}(x) = \Lambda(x)$, for all k when $N \to \infty$. In this case, DE can be used to predict the threshold, $G^\star$, for B-CSA based on the original degree distribution $\Lambda(x)$, as explained in Section 2.3. However, when the number of slots is small, the difference between the original and the different induced distributions is significant, as illustrated with the example above.

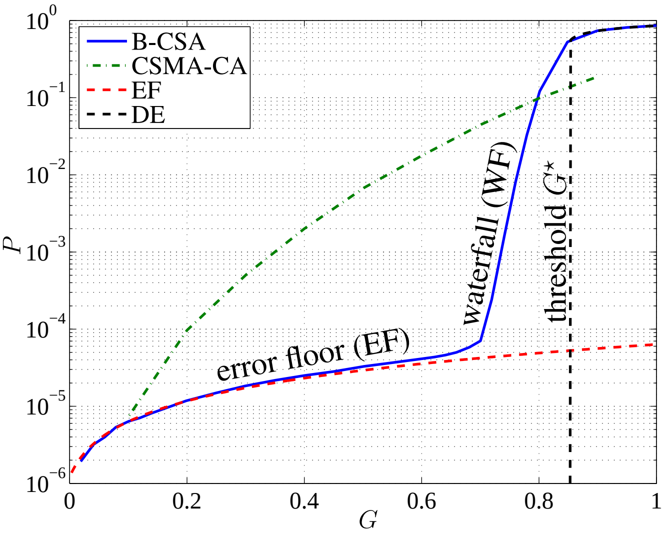


Figure 3: PLR vs. channel load for CSMA-CA (dash-dotted) and B-CSA (solid) with $N = 315$.

Comparing B-CSA with CSMA-CA is not straightforward for several reasons. First, time is not structured in slots in CSMA-CA and new definitions of channel load and PLR are therefore needed. This also hinders modeling users' mobility. Second, the behavior of each user in a CSMA-CA system depends on the behavior of its neighbors, whereas users in B-CSA act independently. Thus, to estimate the performance of an individual user in a CSMA-CA system, the entire network needs to be modeled. Third, the performance of CSMA-CA is affected by the hidden terminal problem since acknowledgments are not used in VANETs. Hence, a proper modeling requires specification of: sensing threshold, path loss, transmitted power, decoding model with signal-to-interference-plus-noise ratio (SINR), and actual network geometry. Instead, in [23] we introduce a simplified system model which represents the best-case scenario in terms of the performance of CSMA-CA. It is easy to implement and compare with B-CSA.

Assuming that each user in the VC network continuously transmits 10 CAM packets per second, i.e., a frame length of $T_\text{f} = 0.1$ seconds. Assuming that each message contains 200 bytes of information, and that the data rate in 802.11p is the default 6 Mbit/s [5], results in a frame length with $N = 315$ slots. To compare CSMA-CA (that is today's standard in VANETs) with B-CSA we use the distribution $\Lambda_\text{B}(x) \triangleq 0.87x^3 + 0.13x^8$. The parameters in this setup are taken from the PHY layer in [5] and all details on the comparison can be found in [23]. The simulated PLR performance of the two protocols is shown in Fig. 3 for $N = 315$. The solid and the dash-dotted curves show simulation results for B-CSA and CSMA-CA, respectively. Similarly to low-density parity-check (LDPC) codes, a finite frame length results in three distinct regions in the PLR of B-CSA as seen in Fig. 3; the *error floor* (EF) region for $G \leq 0.7$, the *waterfall* (WF) region for $0.7 < G \leq 0.85$, and the region with very high PLR when $G > 0.85$, where the EF is caused by the stopping sets present in the graph [17]. It is clear that the simulated performance of B-CSA for $N = 315$ is far from the threshold, $G^\star$, predicted by DE (dashed black curve), assuming $N = \infty$, especially in the EF region. It can be seen from Fig. 3 that B-CSA significantly outperforms CSMA-CA for medium to high channel loads. For example, B-CSA achieves a PLR of $P = 10^{-4}$ at channel load $G = 0.71$ (222 vehicles). CSMA-CA achieves the same reliability at $G = 0.20$ (64 vehicles), i.e., B-CSA can support more than three times as many users as CSMA-CA for this reliability. For heavily loaded networks ($G > 0.8$), CSMA-CA shows better performance. However, in this case both protocols provide a poor reliability, $P > 0.1$, which is unacceptable in VANETs.

3 Project Description

In summary, VC networks require: i) uncoordinated medium access since the network is so dynamic and has so many users that it is unfeasible that all of them are coordinated, especially since there might not necessarily be a BS nearby, ii) all-to-all broadcast, since all vehicles should transmit to and receive from all other vehicles, iii) high reliability, i.e., all messages should be received with hardly any errors, especially since there is no room for acknowledgments or retransmissions, and iv) low latency since the messages carry information about the vehicles' position and intensions and therefore the information needs to be up to date. The preliminary simulation results shown in Fig. 3 indicate that B-CSA fulfills all these four requirements. In other words, B-CSA is believed to be a new paradigm that can be used as the medium access protocol for a large number of uncoordinated all-to-all broadcast users, that in the example achieve $P < 10^{-4}$ within a strict deadline of $T_{\text{f}} = 0.1$ seconds. The identified main tasks that coincide with the goals listed in Section 1 can be summarized as follows:

Task 1: **Performance prediction**

As discussed in Section 2, previous work on CSA has been focused on predicting the performance in the asymptotic regime $N \to \infty$ using DE [14,21]. However, as evident by the simulation results of CSA and B-CSA systems in Figs. 2–3, the prediction using DE is not accurate for finite frame lengths. The first task is therefore to develop tools to accurately predict the PLR for arbitrary distributions in the EF region for finite frame length, e.g., to get a curve similar to the red dashed curve in Fig. 3. This prediction should not only depend on the distribution but also the finite frame length N. Furthermore, as explained in Section 2.3, DE can be used to predict the PLR for a finite number of iterations in the SIC process. It would be advantages to do so even for finite N. An ultimate goal is to predict the performance in both the EF and the WF regions for a finite frame length and a specific number of iterations. LDPC codes are in most cases designed to have a graph excluding stopping sets consisting of length-4 cycles, since they contribute substantially to the EF. However, in CSA systems the graph cannot be designed, since it is built up by the random repetition degree the users pick specified by the distribution. Actually, in CSA the graph is different from frame to frame and the receiver build up the knowledge of the graph while running the SIC procedure. For that reason, length-4 cycles are present in stopping sets and contribute to the EF. We believe that similar to the EF prediction for LDPC codes [17], stopping sets can be identified and used for predicting the performance in the EF for finite N. In [24] we have some preliminary results on how to estimate the PLR in the EF region based on stopping sets found by extensive simulations, as will be briefly discussed in Section 5. However, in Task 1 we would like to perform a thorough and more systematic search and analytical analysis of stopping sets, e.g., finding all stopping sets that include a certain number of VNs or CNs for any arbitrary distribution and find expressions of their probabilities, and not only for distributions with large fractions of degree-2 and degree-3 users as we did in [24]. Here we believe that stopping set enumeration tools similar to the ones used for finding stopping sets of LDPC codes can be used [25].

Outcomes: Tools to predict the PLR, in both the EF and WF regions, of CSA and B-CSA systems with any arbitrary distribution for a finite frame length and a fixed number of iterations.

Task 2: **Optimization**

It is clear that the performance depends on the distribution $\Lambda(x)$. In [14,19,21] DE was used to find optimal distributions in the asymptotic regime $N \to \infty$. Using the results from Task 1, optimal distributions can be found for CSA and B-CSA with finite frame lengths N. For VC networks it is important to meet a certain PLR with a specified maximum latency. For example, the simulation result in Fig. 3 is based on a frame length of $T_{\text{f}} = 0.1$ seconds, which corresponds to that all vehicles transmit 10 messages per second. If the requirement is to fulfill a target PLR of $P < 10^{-4}$ with this frame length, the distribution $\Lambda_{\text{B}}(x)$ seems to be a good choice, but maybe there are better distributions? This can be formulated as follows: based on the performance prediction tool developed in Task 1, find the distribution that maximizes the channel load G for a target PLR P (or that minimizes P for a target G). The performance prediction used could, e.g., be to combine the prediction of the EF for finite N with the threshold for $N \to \infty$. Another alternative is to use the EF prediction at a certain channel load, e.g., $G = 0.5$. If the EF prediction looks something like the dashed red curve in Fig. 3, it might be easier to optimize the distribution when $G \to 0$ or $G \to 1$, even though these two values are not interesting for a real system, they might give insight to how the distributions should be chosen. The solid curve in Fig. 3 represents the average performance in the system. However, the individual performance depends on the repetition degree. The chance of a user to be resolved by other users increases if the user transmits more, but at the same time the chance to resolve other users decreases since there are many slots that are not available due to the half-duplex assumption [23]. This double unequal error protection can be used in the optimization to give different

users different priority, or error protection.
Outcomes: Based on the performance prediction tool in Task 1, find the optimal distribution in terms of a tradeoff between the channel load, G, and the PLR, P, to meet a certain latency T_{f}.

Task 3: **Realistic conditions**

In the setup and analysis described above, there are some simplifying assumptions: i) all users are assumed to be both frame and slot synchronized. This can be achieved by using, e.g., Global Positioning System (GPS), which provides an absolute time reference for all users, ii) the receiver can always detect if a slot has collisions or not, iii) if there is no collision in the slot the receiver can correctly decode the transmitting user, i.e., there are no errors due to a bad channel, high level of noise, or wrong estimation of channel parameters, iv) the SIC is ideal, i.e., all necessary estimation of channel parameters (channel gain, time offset, frequency offset, phase offset, etc.) are assumed to be perfect so that the removal of previously decoded users from the received signal is complete. In other words, the only source of error is the stopping sets prohibiting more users from being resolved. In [14, 21] it is demonstrated that these assumption can be fulfilled for a CSA system using standard QPSK modulation over an additive white Gaussian noise (AWGN) channel with random delay, random frequency offset, and random phase. For this scenario, the SIC can perfectly resolve up to eight users without losing more than one dB in signal-to-noise ratio (SNR). The third Task in this project involves investigations about what happens if some (or all) of the above assumptions are lifted. For example, if the users are only slot synchronized, and not frame synchronized, the users can pick random slots as soon as there is a packet to transmit instead of waiting to the start of the next frame. This will reduce the delay to access the channel, but it will make the receiving algorithm more complicated. The PHY layer in 802.11p is based on orthogonal frequency-division multiplexing (OFDM). How many users can realistically be resolved using SIC together with this PHY layer assuming that also time offset, frequency offset, and phase offset have to be predicted and tracked together with the channel estimation throughout the packet? Also, what happens to the performance prediction in Task 1 and the optimization in Task 2 if only a finite number of users can be resolved per time slot, instead of an unlimited number of users? The users in real VC networks do not experience just an AWGN channel but a more realistic fast fading channel. If the users that collide in a time slot has very different SINR, maybe it is possible to still decode some of the users?
Outcomes: The performance prediction in Task 1 and the optimization in Task 2 are both assuming ideal conditions in terms of synchronization and channel estimation. In Task 3, these assumptions are lifted and the investigation will show the performance (and limitations) of the approach under more realistic conditions.

3.1 Deliminations

The project focuses on the medium access protocol CSA and will not consider updates to the PHY layer of 802.11p (even though this PHY layer is used in Task 3 to verify that the suggested SIC works in reality for 802.11p). Here only the end-to-end latency between two MAC layers including one wireless link is considered. We are not considering several hops or any other routing. Other delimitations include security aspects, practical experiments, as well as novel channel estimation techniques and network synchronization (even though standard channel estimation and synchronization are used to verify the realistic conditions in Task 3).

4 Significance

Around 1.25 million deaths caused by traffic injuries occur worldwide every year according to the World Health Organization [26]. That means that one person is killed every 25 seconds. The prediction is that by 2020 the number of deaths caused by road traffic crashes will have increased to 1.9 million people if no actions are taken. If reliable VC can reduce these numbers with even a small fraction, it will be of great significance. In addition, we believe that the knowledge this project build on CSA can also be used to improve other communication systems that are critical, requires low-latency, and are highly dynamic (or a subset of the above) to make the significance of this project even stronger.

5 Preliminary Results

Both applicants have strong track records in code design that is highly related to this project. For example, in our joint publications [27, 28], later on further developed in [29–31], we designed, analyzed, and optimized a generalized parallel and serially concatenated convolutional code in both the EF region (based on union bounds) and in the WF region (based on extrinsic information transfer (EXIT) chart analysis). This is a perfect background to tackle the prediction of the performance of B-CSA in both the EF and the WF region specified in Task 1 of this project. In fact, we already have some preliminary results presented in [24], where we suggest a way to predict the EF in CSA systems. The prediction is based on simulation to identify common stopping sets in the underlying graph. Identifying all stopping sets and calculating their corresponding probabilities in a systematic way is not straightforward in general. However, restricting the search to distributions with large fractions of degree-2 and degree-3 users and by running extensive simulations for such distributions, we identified eight stopping sets and their corresponding probabilities that contribute the most to the EF.

As mentioned in Section 3, we also have some very recent preliminary work where we derive the induced distributions for B-CSA [23]. Combining these distributions with the EF estimation outlined in [24] we can also predict the EF performance in B-CSA systems. The red dashed curve in Fig. 3 is in fact the EF prediction for the B-CSA system using $\Lambda_{\mathrm{B}}(x)$ [23]. Furthermore, $\Lambda_{\mathrm{B}}(x)$ is found by an *ad hoc* optimization outlined in [23] for a channel load of $G = 0.5$. However, in this project the optimization criteria should be better specified and motivated and the optimization should be based on the outcome of Task 1, potentially combined with the more realistic conditions in Task 3.

The main applicant has also long experience in advanced algorithm design for WiFi 802.11 (that is currently used in VC networks as the standard PHY and MAC layers – with only small modifications) from working more than four years as Principal Design Engineer at Quantenna Communications, Fremont, CA. In relation to Task 3, we have also proposed a channel estimation technique in 802.11p for highly time-varying vehicular channels [32], which also resulted in a patent [33], that could be used together with CSA as the medium access protocol.

6 International and National Collaboration

The Communication Systems (ComSys) group at the Department of Signals and Systems, Chalmers University of Technology, is the largest research group in communications in Sweden, and one of the leading research groups in communications in Europe. The group includes 8 Professors, 8 Postdocs (2 of them with Marie Curie Individual Fellowships), and around 30 PhD students. ComSys' members originate from 14 different countries (Sweden, Germany, Spain, Austria, Italy, Belgium, Romania, Russia, Iran, India, China, Vietnam, Mexico, and Peru).

The applicants have already a proven track record of working together, as evidenced by joint publications. In addition, the applicants have ongoing collaborations within the area of CSA with Prof. Petar Popovski (University of Aalborg) and Dr. Gianluigi Liva (German Aerospace Center, DLR), where research visits are planned in both directions. The applicants have also ongoing collaboration within the area of coding and codes on graphs with Prof. Henry D. Pfister (Duke University), Prof. Iryna Andriyanova (ENSEA/University of Cergy-Pontoise/CNRS, France), Prof. Michael Lentmaier (Lund University), Dr. Eirik Rosnes (University of Bergen, Norway), Prof. Lars K. Rasmussen (KTH, Stockholm), and Dr. Alex Alvarado (UCL, London), to name a few. Moreover, ComSys has collaborations with other universities in Sweden (KTH Stockholm, Lund, Linköping), USA (Stanford, Princeton, MIT, Texas A&M, Notre Dame, Northwestern), Switzerland (EPFL, ETH), Germany (TUM, TUB, RWTH Aachen), France (ENST Bretagne, EURECOM), UK (Cambridge), Italy (Politecnico di Torino, University of Parma), Spain (UPC), Finland (University of Aalto), and Australia (Institute for Telecommunications Research and UNSW). The plan for the PhD student working in this project is to spend time at a highly recognized research institute.

The strong position of the ComSys group in the European research community is manifested by the participation in several EU-funded networks: FP4 (FRAMES), FP5 (ULTRAWAVES), FP6 (WINNER, WINNER II, NEWCOM), FP7 (NEWCOM++, ARTIST4G, METIS), COST (273, 289, 2100), and CELTIC

WINNER+. On the national arena, the ComSys group is a member of many centers and projects, together with many large companies (Ericsson, Volvo, ABB, SP, Huawei, Kapsch), small companies (Qamcom, Bluetest, Smarteq), research institutes, and universities. For example the the Fibre Optic Communications Research Centre (FORCE) and the Chalmers Antenna Systems Excellence (Chase) centre, to name a few.

The applicants have also been involved in organizing the 2012 International Symposium on Turbo Codes & Iterative Processing, the 2013 Swedish Communication Technologies Workshop (Swe-CTW), and the 2015 International Conference on Localization and GNSS (all on Chalmers campus in Gothenburg). In addition, Prof. Brännström and Prof. Graell i Amat are both Co-Chairs of the 2016 IEEE European School of Information Theory, that will also be held on Chalmers campus in Gothenburg.

7 Other Grants

The main applicant, F. Brännström, is the main applicant of the VR project 2011-5950 (see the Scientific report), that ends in 2015. There is no overlap between that project and this proposal.

References

[1] "Scenarios, requirements and KPIs for 5G mobile and wireless system," METIS deliverable D1.1, Apr. 2013, [Online]. Available at https://www.metis2020.com/wp-content/uploads/deliverables/METIS_D1.1_v1.pdf.

[2] G. Fettweis and S. Alamouti, "5G: Personal mobile Internet beyond what cellular did to telephony," *IEEE Commun. Magazine*, vol. 52, no. 2, pp. 140–145, Feb. 2014.

[3] Erik G. Ström, Hannes Hartenstein, Paolo Santi, and Werner Wiesbeck, "Vehicular communications [scanning the issue]," *Proceedings of the IEEE*, vol. 99, no. 7, pp. 1158–1161, July 2011.

[4] C.F. Mecklenbrauker, A.F. Molisch, J. Karedal, F. Tufvesson, A. Paier, L. Bernado, T. Zemen, O. Klemp, and N. Czink, "Vehicular channel characterization and its implications for wireless system design and performance," *Proceedings of the IEEE*, vol. 99, no. 7, pp. 1189–1212, July 2011.

[5] IEEE Std. 802.11-2012, "Part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications," Tech. Rep., Mar. 2012.

[6] Thomas Zemen, Laura Bernadó, Nicolai Czink, and Andreas F. Molisch, "Iterative time-variant channel estimation for 802.11p using generalized discrete prolate spheroidal sequences," *IEEE Trans. Veh. Tech.*, vol. 61, no. 3, pp. 1222–1233, Mar. 2012.

[7] Giuseppe Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000.

[8] Marc Torrent-Moreno, Jens Mittag, Paolo Santi, and Hannes Hartenstaein, "Vehicle-to-vehicle communication: Fair transmit power control for safety-critical information," *IEEE Trans. Veh. Tech.*, vol. 58, no. 7, pp. 3684–3703, Sep. 2009.

[9] Ching-Ling Huang, Yaser Pourmohammadi, Raja Sengupta, and Hariharan Krishnan, "Intervehicle transmission rate control for cooperative active safety system," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 3, pp. 645–658, Sep. 2011.

[10] Katrin Bilstrup, Elisabeth Uhlemann, Erik Ström, and Urban Bilstrup, "On the ability of the 802.11p MAC method and STDMA to support real-time vehicle-to-vehicle communication," *EURASIP Journal on Wireless Commun. and Networking*, vol. 2009, pp. 1–13, Apr. 2009.

[11] N. Abramson, "The ALOHA System – Another alternative for computer communications," in *Proc. 1970 Fall Joint Computer Conf.*, 1970, vol. 37, pp. 281–284.

[12] L. G. Roberts, "ALOHA packet system with and without slot and capture," *SIGCOMM Comput. Commun. Rev.*, vol. 5, no. 2, pp. 28–42, Apr. 1975.

[13] G. L. Choudhury and S. S. Rappaport, "Diversity ALOHA – A random access scheme for satellite communications," *IEEE Trans. Commun.*, vol. 1, no. 3, pp. 450–457, Mar. 1983.

[14] G. Liva, "Graph-based analysis and optimization of contention resolution diversity slotted ALOHA," *IEEE Trans. Commun.*, vol. 59, no. 2, pp. 477–487, Feb. 2011.

[15] E. Casini, R. De Gaudenzi, and O. del Rio Herrero, "Contention resolution diversity slotted ALOHA (CRDSA): An enhanced random access scheme for satellite access packet networks," *IEEE Trans. Wireless Commun.*, vol. 6, no. 4, pp. 1408–1419, Apr. 2007.

[16] O. del Rio Herrero and R. De Gaudenzi, "A high-performance MAC protocol for consumer broadband satellite systems," in *Proc. 27th AIAA International Commun. Satellite Syst. Conf. (ICSSC)*, Edinburgh, UK, June 2009.

[17] C. Di, D. Proietti, I. E. Telatar, T. J. Richardson, and R. L. Urbanke, "Finite-length analysis of low-density parity-check codes on the binary erasure channel," *IEEE Trans. Inf. Theory*, vol. 48, no. 6, pp. 1459–1473, June 2002.

[18] T. J. Richardson, A. Shokrollahi, and R. L. Urbanke, "Design of capacity-approaching irregular low-density parity-check codes," *IEEE Trans. Inf. Theory*, vol. 47, no. 2, pp. 619–637, Feb. 2001.

[19] K. R. Narayanan and H. D. Pfister, "Iterative collision resolution for slotted ALOHA: an optimal uncoordinated transmission policy," in *Proc. Int. Symp. on Turbo Codes and Iterative Information Processing*, Gothenburg, Sweden, Aug. 2012.

[20] Enrico Paolini, Gianluigi Liva, and Marco Chiani, "High throughput random access via codes on graphs: Coded slotted ALOHA," in *Proc. IEEE Int. Conf. Commun.*, Kyoto, Japan, June 2011.

[21] E. Paolini, G. Liva, and M. Chiani, "Coded slotted ALOHA: A graph-based method for uncoordinated multiple access," *submitted to IEEE Trans. Inf. Theory*, Jan. 2014, available at http://arxiv.org/abs/1401.1626.

[22] "Vehicular communications; basic set of applications; part 2: Specification of cooperative awareness basic service," ETSI TS 102 637-2, V1.2.1, 2011, [Online]. Available at http://www.etsi.org/deliver/etsi_ts/102600_102699/10263702/01.02.01_60/ts_10263702v010201p.pdf.

[23] Mikhail Ivanov, Fredrik Brännström, Alexandre Graell i Amat, and Petar Popovski, "All-to-all broadcast for vehicular networks based on coded slotted ALOHA," *to appear in IEEE Int. Conf. Commun. (ICC)*, London, UK, June 2015, [Online]. Available at http://arxiv.org/pdf/1412.2888v1.pdf.

[24] Mikhail Ivanov, Fredrik Brännström, Alexandre Graell i Amat, and Petar Popovski, "Error floor analysis of coded slotted ALOHA over packet erasure channels," *IEEE Commun. Lett.*, vol. 19, no. 3, pp. 419–422, Mar. 2015.

[25] E. Rosnes and O. Ytrehus, "An efficient algorithm to find all small-size stopping sets of low-density parity-check matrices," *IEEE Trans. Inf. Theory*, vol. 55, no. 9, pp. 4167–4178, Sept. 2009.

[26] "Road traffic injuries," *World Health Organization, Fact sheet N°358*, Mar. 2013.

[27] A. Graell i Amat, F. Brännström, and L. K. Rasmussen, "Design of rate-compatible serially concatenated convolutional codes," in *Proc. Int. Symp. Turbo Codes and Related Topics*, Munich, Germany, Apr. 2006.

[28] A. Graell i Amat, F. Brännström, and L. K. Rasmussen, "On the design of rate-compatible serially concatenated convolutional codes," *European Trans. Telecommun.*, vol. 18, pp. 519–527, Aug. 2007.

[29] F. Brännström, A. Graell i Amat, and L. K. Rasmussen, "Analysis and design of concatenated codes," in *Proc. NEWCOM-ACoRN Joint Workshop*, Vienna, Austria, Sept. 2006.

[30] F. Brännström, A. Graell i Amat, and L. K. Rasmussen, "A general structure for rate-compatible concatenated codes," *IEEE Commun. Lett.*, vol. 11, no. 5, pp. 437–439, May 2007.

[31] A. Graell i Amat, L. K. Rasmussen, and F. Brännström, "Unifying analysis and design of rate-compatible concatenated codes," *IEEE Trans. Commun.*, vol. 59, no. 2, pp. 343–351, Feb. 2011.

[32] K. K. Nagalapur, F. Brännström, and E. G. Ström, "On channel estimation for 802.11p in highly time-varying vehicular channels," in *IEEE Int. Conf. Commun. (ICC)*, Sydney, Australia, June 2011, pp. 5659–5664.

[33] K. K. Nagalapur, F. Brännström, and E. G. Ström, "Method to introduce complementing training symbols into a 802.11p ofdm frame in vehicular communications," *Patent Cooperation Treaty (PCT)*, Sept. 2014.

Interdisciplinarity

My application is interdisciplinary

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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.

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Scientific Report

1. Project Information

The project "MIMO-BICM: Fundamentals, Analysis, and Design" (Swedish Research Council: 2011-5950) with main applicant Prof. Fredrik Brännström and co-applicants Dr. Alex Alvarado and Prof. Erik Agrell was approved for the period Jan 1, 2012, to Dec 31, 2015. The total funding received is 3280 kSEK divided according to: 760 kSEK (2012), 840 kSEK (2013), 840 kSEK (2014), and 840 kSEK (2015). The project money has been mainly used to support a new PhD student Mr. Mikhail Ivanov. It has also partially been used to support Mr. Ivanov's main supervisor (Prof. Fredrik Brännström) and co-supervisors (Dr. Alex Alvarado and Prof. Erik Agrell).

2. Scientific Results

So far the scientific results have been quite large in project 2011-5950. The published papers are listed below in Section 4, and they are all in the most prestigious IEEE journals and conferences.

Papers [1,2] treat the fundamental problem of analytically expressing the exact bit-error rate (BER) of uncoded systems with higher order modulation if the optimal detector that minimizes the BER is used. These fundamental closed form expressions have only previously been known for the simplest constellation with 4 points labeled with Gray labeling.

Papers [3,4] propose a novel way of looking at the well-known trellis coded modulation (TCM) system proposed by Ungerboeck in the 1970s. By identifying equivalent combinations of convolutional encoders and higher order constellations an exhaustive search could be performed listing the combinations that give the best performance in terms of BER, i.e., optimal TCM encoders in contrast to Ungerboeck's design that was exclusively based on one labeling he called set-partitioning.

Papers [5,6] characterize the high signal-to-noise (SNR) asymptotic behavior of bit-interleaved coded modulation (BICM). It is shown that the BICM generalized mutual information (BICM-GMI) has an asymptotic behavior proportional to the Gaussian Q-function, whose argument only depends on the minimum Euclidean distance of the constellation. The results are used to prove Caire's long-standing conjecture that Gray labeling maximizes BICM-GMI for high SNR.

Paper [7] proposes a simple approximation for the BICM-GMI that can be used to perform searches of good labelings for constellations with many points. As an example, a labeling was found for the 32-ary constellation used in the digital video broadcasting (DVB-S2) standard that offer a gain of about 0.15 dB.

Paper [8] studies two decoders for coded modulation systems: i) the maximum likelihood decoder, and ii) the suboptimal bit-wise decoder based on BICM. It is proven that the maximum difference between the decoders is bounded by 1.25 dB using 16QAM, but for a wide range of linear codes (including all rate-1/2 convolutional codes) the loss is zero.

3. Relation to New Proposed Project

As outlined in Section 2, the project 2011-5950 deals with the fundamentals, performance analysis, and design of coded modulation systems and there is no overlap between that project and this proposal.

4. Published Journal and Conference Paper with the Project

[1] M. Ivanov, F. Brännström, A. Alvarado, and E. Agrell, "General BER expression for one-dimensional constellations," in *Proc. IEEE Global Telecommunications Conference (GLOBECOM '12)*, Anaheim, CA, Dec. 2012, pp. 2162–2167.

[2] M. Ivanov, F. Brännström, A. Alvarado, and E. Agrell, "On the exact BER of bit-wise demodulators for one-dimensional constellations," *IEEE Transactions on Communications*, vol. 61, no. 4, pp. 1450–1459, Apr. 2013.

[3] A. Alvarado, A. Graell i Amat, F. Brännström, and E. Agrell, "On the equivalence of TCM encoders," in *Proc. IEEE International Symposium on Information Theory (ISIT '12)*, Cambridge, MA, July 2012, pp. 2401–2405.

[4] A. Alvarado, A. Graell i Amat, F. Brännström, and E. Agrell, "On optimal TCM encoders," *IEEE Transactions on Communications*, vol. 61, no. 6, pp. 2178–2189, June 2013.

[5] A. Alvarado, F. Brännström, E. Agrell, and T. Koch, "High-SNR asymptotics of mutual information for discrete constellations," in *Proc. IEEE International Symposium on Information Theory (ISIT '13)*, Istanbul, Turkey, July 2013, pp. 2274–2278.

[6] A. Alvarado, F. Brännström, E. Agrell, and T. Koch, "High-SNR asymptotics of mutual information for discrete constellations with applications to BICM," *IEEE Transactions on Information Theory*, vol. 60, no. 2, pp. 1061–1076, Feb. 2014.

[7] A. Alvarado, F. Brännström, and E. Agrell, "A simple approximation for the bit-interleaved coded modulation capacity," *IEEE Communications Letters*, vol. 18, no. 3, pp. 495–498, Mar. 2014.

[8] M. Ivanov, A. Alvarado, F. Brännström, and E. Agrell, "On the asymptotic performance of bit wise decoders for coded modulation," *IEEE Transactions on Information Theory*, vol. 60, no. 5, pp. 2796–2804, May 2014.

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	Fredrik Brännström	25
2	Participating researcher	Alexandre Graell i Amat	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	Fredrik Brännström	25	252,000	261,000	270,000	280,000	1,063,000
2	Participating researcher	Alexandre Graell i Amat	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	Conference	(1-2 per year)	30,000	60,000	60,000	60,000	210,000
3	Research visit	(4 months visit after Lic + 2 months in last year)			60,000	20,000	80,000
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		116,000	117,000	152,000	143,000	528,000

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	116,000	117,000	152,000	143,000	528,000		528,000
Depreciation costs					0		0
Premises	68,000	71,000	73,000	76,000	288,000		288,000
Subtotal	1,131,000	1,169,000	1,239,000	1,270,000	4,809,000	0	4,809,000
Indirect costs	348,000	360,000	372,000	385,000	1,465,000		1,465,000
Total project cost	1,479,000	1,529,000	1,611,000	1,655,000	6,274,000	0	6,274,000

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 (Fredrik Brännström) will participate in the project with 25% and the co-applicant (Alexandre Graell i Amat) 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 participants are purchased in the begining of the project (20 kSEK each). One conference visit the first year and two conference visits the following three years, each with an estimated cost of 30 kSEK. 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

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).

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**.

Publication list

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

[1] F. Brännström, L. K. Rasmussen, and A. J. Grant, "Convergence analysis and optimal scheduling for multiple concatenated codes," *IEEE Transactions on Information Theory*, vol. 51, no. 9, pp. 3354–3364, Sept. 2005.
Number of citations: 143.

[2] F. Brännström, T. M. Aulin, and L. K. Rasmussen, "Iterative detectors for trellis-code multiple-access," *IEEE Transactions on Communications*, vol. 50, no. 9, pp. 1478–1485, Sept. 2002.
Number of citations: 58.

[3] F. Brännström, "Convergence analysis and design of multiple concatenated codes," Ph.D. dissertation, Chalmers University of Technology, Gothenburg, Sweden, Mar. 2004.
Number of citations: 54.

[4] F. Brännström, T. M. Aulin, and L. K. Rasmussen, "Iterative multi-user detection of trellis code multiple access using *a posteriori* probabilities," in *Proc. IEEE International Conference on Communications (ICC '01)*, vol. 1, Helsinki, Finland, June 2001, pp. 11–15.
Number of citations: 46.

[5] F. Brännström, T. M. Aulin, and L. K. Rasmussen, "Constellation-constrained capacity for trellis code multiple access systems," in *Proc. IEEE Global Telecommunications Conference (GLOBECOM '01)*, vol. 2, San Antonio, TX, Nov. 2001, pp. 791–795.
Number of citations: 24.

2 Peer-reviewed Journal Papers

[6] W. Sun, E. G. Ström, F. Brännström, and M. R. Gholami, "Random broadcast based distributed consensus clock synchronization for mobile networks," *IEEE Transactions on Wireless Communications*, (to appear) Feb. 2015.
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, Apr. 2015, **Invited paper**.
Number of citations: 0.

[8] (★)M. Ivanov, F. Brännström, A. Graell i Amat, and P. Popovski "Error floor analysis of coded slotted ALOHA over packet erasure channels," *IEEE Communications Letters*, vol. 19, no. 3, pp. 419–422, Mar. 2015.
Number of citations: 1.

[9] 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.

[10] M. Ivanov, A. Alvarado, F. Brännström, and E. Agrell, "On the asymptotic performance of bit-wise decoders for coded modulation," *IEEE Transactions on Information Theory*, vol. 60, no. 5, pp. 2796–2804, May 2014.
Number of citations: 3.

[11] A. Alvarado, F. Brännström, and E. Agrell, "A simple approximation for the bit-interleaved coded modulation capacity," *IEEE Communications Letters*, vol. 18, no. 3, pp. 495–498, Mar. 2014.
Number of citations: 3.

[12] A. Alvarado, F. Brännström, E. Agrell, and T. Koch, "High-SNR asymptotics of mutual information for discrete constellations with applications to BICM," *IEEE Transactions on Information Theory*, vol. 60, no. 2, pp. 1061–1076, Feb. 2014.
Number of citations: 11.

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

[14] M. Ivanov, F. Brännström, A. Alvarado, and E. Agrell, "On the exact BER of bit-wise demodulators for one-dimensional constellations," *IEEE Transactions on Communications*, vol. 61, no. 4, pp. 1450–1459, Apr. 2013.
Number of citations: 5.

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

[16] F. Brännström, L. K. Rasmussen, and A. J. Grant, "Optimal puncturing ratios and energy allocation for multiple parallel concatenated codes," *IEEE Transactions on Information Theory*, vol. 55, no. 5, pp. 2062–2077, May 2009.
Number of citations: 12.

[17] F. Brännström and L. K. Rasmussen, "Classification of unique mappings for 8PSK based on bit-wise distance spectra," *IEEE Transactions on Information Theory*, vol. 55, no. 3, pp. 1131–1145, Mar. 2009.
Number of citations: 20.

[18] D. P. Shepherd, F. Brännström, F. Schreckenbach, Z. Shi, and M. C. Reed "Adaptive optimization of an iterative multiuser detector for turbo-coded CDMA," *IEEE Transactions on Wireless Communications*, vol. 7, no. 11, pp. 4284–4293, Nov. 2008.
Number of citations: 8.

[19] (★)A. Graell i Amat, F. Brännström, and L. K. Rasmussen, "On the design of rate-compatible serially concatenated convolutional codes," *European Transactions on Telecommunications* vol. 18, pp. 519–527, Aug. 2007, **Invited paper**.
Number of citations: 18.

[20] (★)F. Brännström, A. Graell i Amat, and L. K. Rasmussen, "A general structure for rate-compatible concatenated codes," *IEEE Communications Letters*, vol. 11, no. 5, pp. 437–439, May. 2007.
Number of citations: 9.

3 Peer-reviewed Conference Papers

[21] A. Graell i Amat, C. Häger, F. Brännström, and E. Agrell, "Spatially-coupled codes for optical communications: state-of-the-art and open problems," to appear in *Opto Electronics and Communications Conference (OECC)*, Shanghai, China, June/July 2015, **Invited paper**.
Number of citations: 0.

[22] (★)M. Ivanov, F. Brännström, A. Graell i Amat, and P. Popovski, "All-to-all broadcast for vehicular networks based on coded slotted ALOHA," to appear in *IEEE International Conference on Communications (ICC '15) Workshop on Massive Uncoordinated Access Protocols (MASSAP)*, London, UK, June 2015.
Number of citations: 0.

[23] W. Sun, D. Yuan, E. G. Ström, and F. Brännström, "Resource sharing and power allocation for D2D-based safety-critical V2X communications," to appear in *IEEE International Conference on Communications (ICC '15) Workshop on Dependable Vehicular Communications (DVC)*, London, UK, June 2015.
Number of citations: 0.

[24] C. Häger, A. Graell i Amat, Henry D. Pfister, A. Alvarado, F. Brännström, and E.Agrell, "On parameter optimization for staircase codes," in *Proc. Optical Fiber Communication Conference and Exposition (OFC)*, Los Angeles, CA, Mar. 2015.
Number of citations: 0.

[25] W. Sun, E. G. Ström, F. Brännström, Y. Sui, and K. C. Sou "D2D-based V2V communications with latency and reliability constraints," in *Proc. IEEE Global Telecommunications Conference (GLOBECOM '14) Workshop on Ultra-Low Latency and Ultra-High Reliability in Wireless Communications (ULTRA)*, Austin, TX, Dec. 2014, pp. 1414–1419
Number of citations: 0.

[26] C. Häger, A. Graell i Amat, F. Brännström, A. Alvarado, and E.Agrell, "Comparison of terminated and tailbiting spatially coupled LDPC codes with optimized bit mapping for PM-64-QAM," in *Proc. European Conference on Optical Communication (ECOC)*, Cannes, France, Sept. 2014.
Number of citations: 1.

[27] K. K. Nagalapur, F. Brännström, and E. G. Ström, "On channel estimation for 802.11p in highly time-varying vehicular channels," in *Proc. IEEE International Conference on Communications (ICC '14)*, Sydney, Australia, June 2014, pp. 5659–5664.
Number of citations: 0.

[28] C. Häger, A. Graell i Amat, A. Alvarado, F. Brännström, and E. Agrell, "Optimized bit mappings for spatially coupled LDPC codes over parallel binary erasure channels," in *Proc. IEEE International Conference on Communications (ICC '14)*, Sydney, Australia, June 2014, pp. 2064–2069.
Number of citations: 5.

[29] W. Sun, M. R. Gholami, E. G. Ström, and F. Brännström, "Distributed clock synchronization with application of D2D communication without infrastructure," in *Proc .IEEE Global Telecommunications Conference (GLOBECOM '13) Workshop on Device-to-Device (D2D) Communication With and Without Infrastructure*, Atlanta, GA, Dec. 2013, pp. 561–566.
Number of citations: 1.

[30] A. Alvarado, F. Brännström, E. Agrell, and T. Koch, "High-SNR asymptotics of mutual information for discrete constellations," in *Proc. IEEE International Symposium on Information Theory (ISIT '13)*, Istanbul, Turkey, July 2013, pp. 2274–2278.
Number of citations: 3.

[31] W. Sun, F. Brännström, and E. G. Ström, "On clock offset and skew estimation with exponentially distributed delays," in *Proc. IEEE International Conference on Communications (ICC '13)*, Budapest, Hungary, June 2013, pp. 1872–1877.
Number of citations: 1.

[32] W. Sun, E. G. Ström, F. Brännström, and D. Sen, "Long-term clock synchronization in wireless sensor networks with arbitrary delay distributions," in *Proc. IEEE Global Telecommunications Conference (GLOBECOM '12)*, Anaheim, CA, Dec. 2012, pp. 359–364.
Number of citations: 4.

[33] M. Ivanov, F. Brännström, A. Alvarado, and E. Agrell, "General BER expression for one-dimensional constellations," in *Proc. IEEE Global Telecommunications Conference (GLOBECOM '12)*, Anaheim, CA, Dec. 2012, pp. 2162–2167.
Number of citations: 8.

[34] A. Alvarado, A. Graell i Amat, F. Brännström, and E. Agrell, "On the Equivalence of TCM Encoders," in *Proc. IEEE International Symposium on Information Theory (ISIT '12)*, Cambridge, MA, July 2012, pp. 2401–2405.
Number of citations: 7.

[35] A. Alvarado, F. Brännström, and E. Agrell, "High SNR bounds for the BICM capacity," in *Proc. IEEE Information Theory Workshop (ITW '11)*, Paraty, Brazil, Oct. 2011, pp. 360–364.
Number of citations: 17.

[36] F. Brännström and L. K. Rasmussen, "Classification of 8PSK mappings for BICM," in *Proc. IEEE International Symposium on Information Theory (ISIT '07)*, Nice, France, June 2007, pp. 2136–2140.
Number of citations: 6.

[37] R. Milner, L. K. Rasmussen, and F. Brännström, "Recursive LLR combining in iterative multiuser decoding of coded CDMA," in *Proc. Australian Communications Theory Workshop (AusCTW '07)*, Adelaide, Australia, Feb. 2007, pp. 104–109.
Number of citations: 6.

[38] D. P. Shepherd, F. Brännström, and M. C. Reed, "Dynamic scheduling for a turbo CDMA receiver using EXIT charts," in *Proc. Australian Communications Theory Workshop (AusCTW '07)*, Adelaide, Australia, Feb. 2007, pp. 34–38.
Number of citations: 5.

4 Patents

[39] K. K. Nagalapur, F. Brännström, and E. G. Ström, "Method to introduce complementing training symbols into a 802.11p OFDM frame in vehicular communications," Patent Cooperation Treaty (PCT), Sept. 2014.

[40] F. Brännström and A. Goldsmith, "Low complexity LDPC decoding," United States Patent No. US 8,407,551 B2, Mar. 26, 2013.

[41] F. Farrokhi, A. Goldsmith, F. Brännström, and B. Rezvani, "Mitigating interference in a coded communication system," United States Patent No. US 8,111,790 B2, Feb. 7, 2012.

[42] F. Brännström and A. Goldsmith, "System and method for decreasing decoder complexity," United States Patent No. US 8,091,012 B2, Jan. 3, 2012.

[43] F. Brännström, A. Goldsmith, F. Farrokhi, and B. Rezvani, "Demodulation technique for GFSK and DPSK," United States Patent No. US 8,090,060 B2, Jan. 3, 2012.

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.
Number of citations: 12

[31] A. Graell i Amat, G. Montorsi, F. Vatta, "Design and performance analysis of a new class of rate compatible serially concatenated convolutional codes," *IEEE Transactions on Communications*, vol. 57, no. 8, pp. 2280–2289, August 2009.
Number of citations: 19

[32] 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

[33] A. Graell i Amat, F. Vatta, G. Montorsi, "Analysis and comparison of some recent classes of turbo like codes for the upcoming DVB standards," *Journal of Communications Software and Systems*, vol. 4, no. 2, pp. 150–158, June 2008. **Invited paper.**
Number of citations: 0

[34] A. Graell i Amat, F. Brännström, Lars K. Rasmussen, "On the design of rate-compatible serially concatenated convolutional codes," *European Transactions on Telecommunications*, vol. 18, no. 5, pp. 519–527, August 2007. **Invited paper.**
Number of citations: 18

[35] F. Brännström, A. Graell i Amat, Lars K. Rasmussen, "A general structure for rate-compatible concatenated codes," *IEEE Communications Letters*, vol. 11, no. 5, pp. 437–439, May 2007.
Number of citations: 9

[36] A. Graell i Amat, A. Tarable, "On the design of space-time trellis codes for transmit-correlated fading channels," *IEEE Transactions on Communications*, vol. 55, no. 1, pp. 112–121, January 2007.
Number of citations: 3

3 Peer-reviewed Conference Papers

[37] A. Graell i Amat, C. Häger, F. Brännström, E. Agrell, "Spatially-Coupled Codes for Optical Communications: State-of-the-Art and Open Problems," in *Proc. 20th OptoElectronics and Communications Conference, OECC'15, special session on "Optical Transmission Systems and Subsystems"*, Shanghai, China, June 28-July 2, 2015. **Invited paper**.
Number of citations: 0

[38] M. Ivanov, F. Brännström, A. Graell i Amat, P. Popovski, "All-to-all Broadcast for Vehicular Networks Based on Coded Slotted ALOHA," in *Proc. IEEE International Conference on Communications – Workshop on Massive Uncoordinated Access Protocols, ICC 2015*, London, UK, June 2015.
Number of citations: 0

[39] R. Krishnan, M. R. Khanzadi, N. Krishnan, Y. Wu, A. Graell i Amat, T. Eriksson, R. Schober, "Large-Scale Analysis of Linear Massive MIMO Precoders in the Presence of Phase Noise," in *Proc. IEEE International Conference on Communications – Workshop on 5G & Beyond, ICC 2015*, London, UK, June 2015.
Number of citations: 0

[40] C. Häger, A. Graell i Amat, Henry D. Pfister, A. Alvarado, F. Brännström, E. Agrell, "On Parameter Optimization for Staircase Codes," in *Proc. Optical Fiber Communication Conference and Exposition, OFC 2014*, Los Angeles, CA, March 2015.
Number of citations: 0

[41] C. Lindberg, A. Graell i Amat, H. Wymeersch, “Distributed Compressed Sensing for Sensor Networks with Packet Erasures,” in *Proc. IEEE Global Conference on Communications, GLOBECOM 2014*, Austin, Texas, December 2014.
Number of citations: 0

[42] A. Graell i Amat, S. Moloudi, M. Lentmaier, “Spatially Coupled Turbo Codes: Principles and Finite Length Performance”, in *Proc IEEE International Symposium on Wireless Communication Systems, ISWCS 2014*, Barcelona, Spain, August 26-29, 2014. **Invited paper**.
Number of citations: 0

[43] A. Graell i Amat, I. Andriyanova, A. Piemontese, “Proving Threshold Saturation for Nonbinary SC-LDPC Codes on the Binary Erasure Channel”, in *Proc. 2014 XXXIth URSI General Assembly and Scientific Symposium, URSI GASS*, Beijing, China, August 16-23, 2014. **Invited paper**.
Number of citations: 0

[44] S. Moloudi, M. Lentmaier, A. Graell i Amat, “Spatially Coupled Turbo Codes”, in *Proc. International Symposium on Turbo Codes & Iterative Information Processing, ISTC 2014*, Bremen, Germany, August 2014.
Number of citations: 5

[45] M. Lentmaier, S. Moloudi, A. Graell i Amat, “Braided Convolutional Codes – A Class of Spatially Coupled Turbo-Like Codes”, in *Proc. International Conference on Signal Processing and Communications, SPCOM 2014*, Bangalore, India, July 22-25, 2014. **Invited paper**.
Number of citations: 2

[46] (★)C. Häger, A. Graell i Amat, A. Alvarado, F. Brännström, E. Agrell, ”Optimized Bit Mappings for Spatially Coupled LDPC Codes over Parallel Binary Erasure Channels", in *Proc. IEEE International Conference on Communications, ICC 2014*, Sydney, Australia, June 2014.
Number of citations: 5

[47] (★)A. Piemontese, A. Graell i Amat, G. Colavolpe, "Nonbinary Spatially-Coupled LDPC Codes on the Binary Erasure Channel", in *Proc. IEEE International Conference on Communications, ICC 2013*, Budapest, Hungary, June 2013.
Number of citations: 9

[48] C. Häger, A. Graell i Amat, A. Alvarado, E. Agrell, ”Constellation Optimization for Coherent Optical Channels Distorted by Nonlinear Phase Noise”, IEEE International Conference on Communications, GLOBECOM 2012, CA, December 2012.
Number of citations: 4

[49] S. Schwandter, A. Graell i Amat, G. Matz, ”Spatially Coupled LDPC Codes for Two-User Decode-and-Forward Relaying”, in *Proc. International Symposium on Turbo Codes & Iterative Information Processing, ISTC 2012*, Gothenburg, Sweden, August 2012.
Number of citations: 4

[50] N. Bitouzé, A. Graell i Amat, E. Rosnes, "Making WOM Codes Decodable using Short Synchronous WOM Codes", in *Proc. IEEE International Symposium on Information Theory, ISIT 2012*, Cambridge, MA, July 2012.
Number of citations: 0

[51] A. Alvarado, A. Graell i Amat, F. Brännström, E. Agrell, "On the Equivalence of TCM Encoders", in *Proc. IEEE International Symposium on Information Theory, ISIT 2012*, Cambridge, MA, July 2012.
Number of citations: 7

[52] H. Farès, A. Graell i Amat, C. Langlais, M. Berbineau, "Two-Level HARQ for Turbo Coded Cooperation: System Retransmission Gain and Optimal Time Allocation", in *Proc. IEEE Wireless Communications and Networking Conference, WCNC 2012*, Paris, March 2012.
Number of citations: 1

[53] B. Makki, A. Graell i Amat, T. Eriksson, "Power Allocation in Repetition Time Diversity Hybrid Automatic Repeat Request Feedback", in *Proc. IEEE Wireless Communications and Networking Conference, WCNC 2012*, Paris, March 2012.
Number of citations: 5

[54] S. Schwandter, H. Farès, A. Graell i Amat, G. Matz, “Error Probability Bounds for Decode-and-Forward Relaying with Two Correlated Sources", in *Proc. IEEE International Conference on Communications,*

GLOBECOM 2011, December 2011.
Number of citations: 1

[55] H. Farès, S. Ould Mohamed, C. Langlais, A. Graell i Amat, M. Berbineau, “MIMO Systems for Turbo Coded Cooperation over Orthogonal and Non-Orthogonal Channels", in *Proc. IEEE 11th International Conference on ITS Telecommunications, ITST 2011*, pp. 453–457, August 2011.
Number of citations: 0

[56] E. Rosnes, M. Helmling, A. Graell i Amat, “Pseudocodewords of Linear Programming Decoding of 3-Dimensional Turbo Codes", in *Proc. IEEE International Symposium on Information Theory, ISIT 2011*, pp. 1643–1647, August 2011.
Number of citations: 3

[57] A. Graell i Amat, E. Rosnes, “On the Minimum Distance Properties of Weighted Nonbinary Repeat Multiple-Accumulate Codes,” in *Proc. 2011 Information Theory and Applications Workshop, ITA 2011*, La Jolla, CA, February 2011. **Invited Paper**.
Number of citations: 0

[58] A. Graell i Amat, I. Land, “Bounds of the Probability of Error for Decode-and-forward Relaying with two Sources,” in *Proc. 6th International Symposium on Turbo Codes & Iterative Information Processing, ISTC 2010*, pp. 196–200, September 2010.
Number of citations: 5

[59] A. Piemontese, A. Graell i Amat, G. Colavolpe, “Information-Theoretic Analysis and Practical Coding Schemes for Spectrally Efficient FDM-CPM Systems,” in *Proc. 6th International Symposium on Turbo Codes & Iterative Information Processing, ISTC 2010*, pp. 275–279, September 2010.
Number of citations: 7

[60] E. Rosnes, A. Graell i Amat, “Performance Analysis of Weighted Nonbinary Repeat Multiple-Accumulate Codes,” in Proc. *6th International Symposium on Turbo Codes & Iterative Information Processing, ISTC 2010*, pp. 236–240, September 2010.
Number of citations: 2

[61] A. Graell i Amat, E. Rosnes, “Stopping Set Analysis for 3-Dimensional Turbo Code Ensembles,” in Proc. *IEEE International Symposium on Information Theory, ISIT 2010*, pp. 2013–2017, June 2010.
Number of citations: 2

[62] I. Land, A. Graell i Amat, L. K. Rasmussen, “Bounding of MAP Decode and Forward Relaying,” in Proc. *IEEE International Symposium on Information Theory, ISIT 2010*, pp. 938–942, June 2010.
Number of citations: 2

[63] R. Youssef, A. Graell i Amat, “Distributed Turbo-Like Codes for Multi-User Cooperative Relay Networks,” in Proc. *IEEE International Conference on Communications, ICC 2010*, pp. 1–5, May 2010.
Number of citations: 10

[64] E. Rosnes, A. Graell i Amat, “Design of a Concatenated Coding Scheme for a Bit-Shift Channel,” in *Proc. IEEE International Conference on Communications, ICC 2010*, pp. 1–5, May 2010.
Number of citations: 1

[65] H. Farès, C. Langlais, A. Graell i Amat, M. Berbineau, “Two-Level HARQ for Turbo Coded Cooperation,” in *Proc. IEEE Vehicular Technology Conference, VTC 2010*, pp. 1–5, May 2010.
Number of citations: 7

[66] A. Graell i Amat, I. Land, L. K. Rasmussen, “Error Bounds for Decode-and-Forward Relaying,” in Proc. *European Wireless 2010, EUW 2010*, pp. 1005–1010, April 2010. **Invited Paper**.
Number of citations: 4

[67] A. Graell i Amat, I. Land, “An Analytical Expression of the Probability of Error for Relaying with Decode-and-forward,” in Proc. *IEEE Information Theory and Applications Workshop*, ITA 2010, pp. 1–5, February 2010. **Invited Paper**.
Number of citations: 7

[68] A. Graell i Amat, E. Rosnes, “Analysis of 3-Dimensional Turbo Code Ensembles,” in Proc. *IEEE Information Theory Workshop, ITW 2010*, pp. 46–50, January 2010.
Number of citations: 3

[69] A. Graell i Amat, E. Rosnes, "Stopping Set Analysis of Repeat Multiple-Accumulate Codes," in Proc. *IEEE International Symposium on Information Theory, ISIT 2009*, pp. 1814–1818, July 2009.
Number of citations: 0

[70] C. Koller, A. Graell i Amat, J. Kliewer, D. J. Costello, Jr., "Trapping Set Enumerators for Repeat Multiple Accumulate Code Ensembles," in Proc. *IEEE International Symposium on Information Theory, ISIT 2009*, pp. 1819–1823, July 2009.
Number of citations: 9

[71] N. Bitouzé, A. Graell i Amat, "Coding for a Non-symmetric Ternary Channel," in Proc. *IEEE Information Theory and Applications Workshop, ITA 2009*, pp. 113–118, February 2009. **Invited Paper**.
Number of citations: 1

[72] J. Kliewer, C. Koller, A. Graell i Amat, D. J. Costello, Jr., "On Trapping Sets for Repeat Accumulate Accumulate Codes," in Proc. *IEEE Information Theory and Applications Workshop, ITA 2009*, pp. 164–168, February 2009.
Number of citations: 0

[73] C. Koller, A. Graell i Amat, J. Kliewer, F. Vatta, D. J. Costello, Jr., "Tuned Turbo Codes," in Proc. *IEEE International Symposium on Information Theory and its Applications*, ISITA 2008, pp. 1–6, December 2008.
Number of citations: 8

[74] F. Vatta, A. Graell i Amat, A. Banerjee, D. J. Costello, Jr., "Nonsystematic Turbo Codes: Design and Bounds on Effective Free Distance," in Proc. *IEEE International Symposium on Information Theory and its Applications, ISITA 2008*, pp. 1–6, December 2008.
Number of citations: 1

[75] C. Koller, A. Graell i Amat, J. Kliewer, F. Vatta, D. J. Costello, Jr., "Hybrid Concatenated Codes with Asymptotically Good Distance Growth," in Proc. *IEEE International Symposium on Turbo Codes & Related Topics, ISTC 2008*, pp. 19–24, September 2008.
Number of citations: 12

[76] A. Graell i Amat, R. Le Bidan, "Rate-Compatible Serially Concatenated Codes with Outer Extended BCH Codes," in Proc. *IEEE Global Conference on Communications, GLOBECOM 2007*, pp. 1476–1481, November 2007.
Number of citations: 3

[77] A. Graell i Amat, G. Montorsi, F. Vatta, "Comparison of Some Powerful Recent Classes of Turbo Like Codes for the Upcoming DVB Standards," in Proc. *IEEE International Conference on Software, Telecommunications and Computer Networks, SOFTCOM 2007*, pp. 1–5, September 2007.
Number of citations: 0

[78] C. Berrou, A. Graell i Amat, Y. Ould Cheikh Mouhamedou, C. Douillard, Y. Saouter, "Adding a Rate-1 Third Dimension to Turbo Codes," in Proc. *IEEE Information Theory Workshop, ITW 2007*, pp. 156–161. September 2007.
Number of citations: 27

[79] A. Graell i Amat, C. Abdel Nour, C. Douillard, "Serially Concatenated Continuous Phase Modulation with Extended BCH Codes," in Proc. *IEEE Information Theory Workshop, ITW 2007*, pp. 1–5, July 2007.
Number of citations: 7

4 Books and Book Chapters

[80] Book co-author, *Codes and turbo codes*, 400 pages (under the direction of Claude Berrou). Springer-Verlag, 2010.
Number of citations: 43

[81] A. Graell i Amat, R. Thobaben, "An introduction to distributed channel coding," in *Channel Coding: Theory, Algorithms, and Applications,* Academic Press Library in Mobile and Wireless Communications. Oxford: Academic Press, 2014. pp. 399-450.
Number of citations: 0

[82] G. Bauch, C. Berrou, D. Declercq, A. Graell i Amat, Y. Ould Cheikh Mouhamedou, Y. Saouter, J. Sayir, M. B.S. Tavares, “Coding,” in *Error control coding for B3G/4G wireless systems: paving the way to IMT-advanced standards*. John Wiley & Sons, 2011.
Number of citations: 9

5 Patents

[83] A. Graell i Amat, R. Pyndiah, R. Youssef, “Methods for transmitting and receiving a digital signal implementing at least one multi-user relay in a cooperative network, and corresponding computer program and devices”, pub. no. WO Patent WO/2011/026998, Intl. App. no. PCT/EP2010/063129, March 10, 2011.

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CV

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

Research education

Dissertation title (swe)
High-rate convolutional codes for high-speed concatenated codes applications: Design and efficient decoding

Dissertation title (en)
High-rate convolutional codes for high-speed concatenated codes applications: Design and efficient decoding

Organisation	Unit	Supervisor
Politecnico di Torino, Italy Not Sweden - Higher Education institutes	Departimento di Elettronica	Sergio Benedetto

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
20203. Kommunikationssystem		2004-12-06

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.

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.

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.