Vetenskapsrådet

Application

2015-03-31

2015-05443	Eriksson, Thomas	NT-14

Information about applicant

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Employer: No current employer

Information about application

Call name: Forskningsbidrag Stora utlysningen 2015 (Naturvetenskap och teknikvetenskap)

Type of grant: Projektbidrag

Focus: Fri

Subject area:

Project title (english): Multidimensional modulation for hardware-constrained communication

Project start: 2016-01-01

Project end: 2019-12-31

Review panel applied for: NT-14, NT-13

Classification code: 20204. Telekommunikation

Keywords: modulation, wireless communication, dirty rf

Funds applied for

Year:	2016	2017	2018	2019
Amount:	1,002,000	1,004,000	1,039,000	1,104,000

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Descriptive data

Project info

Project title (Swedish)*

Flerdimensionell modulation för hårdvarubegränsad kommunikation

Project title (English)*

Multidimensional modulation for hardware-constrained communication

Abstract (English)*

A big challenge in designing a communication system is to make communication links work with real-world analog hardware components, which often must be operated at their very physical limits to fulfill ever-increasing demands on throughput, energy consumption, delay, etc. This is a very active research area today, and virtually every communication link/system today must include techniques to deal with imperfect hardware to make communication possible at all. In current systems, such techniques ("compensating" or "reducing" some problematic effect) are typically applied on top of a system originally designed with a more idealistic view of the hardware; seldom are the most basic parts of the system chosen with imperfect hardware in mind.
We propose a project where multidimensional modulation and demodulation techniques are developed and exploited to improve our control over non-ideal hardware components in single- and multiple-antenna transmissions, and simplify the mitigation of unwanted effects. As we motivate in the proposal, a multidimensional constellation is often a natural choice for improving our control of undesired hardware effects, enabling us to greatly improve our ability to mitigate such effects. As of now, few results can be found in the scientific literature.
The project starts in the lab, where communication hardware is characterized, and the results are refined into theoretical expressions of maximum throughput with hardware constraints. From the theory we will derive multidimensional constellations, optimized for maximal throughput with given hardware constraints.

Popular scientific description (Swedish)*

DAGENS KOMMUNIKATIONSSYSTEM BEGRÄNSAS AV HÅRDVARAN
När man designar ett trådlöst kommunikationssystem måste man ta hänsyn till den hårdvara (såsom förstärkare, oscillatorer mm) som skall användas. För att hänga med i ständigt ökande krav på prestanda, energieffektivitet, fördröjning mm så måste denna hårdvara drivas på gränsen till vad den klarar. Detta skapar problem, och idag kan hårdvaran sägas vara en av de absolut viktigaste begränsningen i moderna system.
Dagens system designas typiskt i grunden för idealiserad hårdvara, och sedan, som en sen uppdatering. lägger man till algoritmer för att lösa problemen som uppstått genom att hårdvaran i verkligheten är långt från ideal. Vi föreslår ett projekt där man designar systemet från grunden till att ta hänsyn till icke-ideal hårdvara, genom att studera hur modulationen kan optimeras. Förhoppningen är att projektet i grunden skall kunna förändra sättet som kommunikationssystem är designade.

Project period

Number of project years*

4

Calculated project time*

2016-01-01 - 2019-12-31

Classifications

Select a minimum of one and a maximum of three SCB-codes in order of priority.

Select the SCB-code in three levels and then click the lower plus-button to save your selection.

SCB-codes*

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

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

Keyword 1*

modulation

Keyword 2*

wireless communication

Keyword 3*

dirty rf

Keyword 4

Keyword 5

Research plan

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*

Inga speciella etiska frågor berörs utöver allmänna, såsom ärlighet vid publicering, jävssituationer som kan uppstå etc.

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

MULTIDIMENSIONAL MODULATION FOR HARDWARE-CONSTRAINED COMMUNICATION

1. EXECUTIVE SUMMARY

A big challenge in designing a communication system is to make communication links work with real-world analog hardware components, which often must be operated at their very physical limits to fulfill ever-increasing demands on throughput, energy consumption, delay, etc. This is a very active research area today, and virtually every communication link/system today must include techniques to deal with imperfect hardware to make communication possible at all. In current systems, such techniques ("compensating" or "reducing" some problematic effect) are typically applied on top of a system originally designed with a more idealistic view of the hardware; seldom are the most basic parts of the system chosen with imperfect hardware in mind.

We propose a project where multidimensional modulation and demodulation techniques are developed and exploited to improve our control over non-ideal hardware components in single- and multiple-antenna transmissions, and simplify the mitigation of unwanted effects. As we motivate in the proposal, a multidimensional constellation is often a natural choice for improving our control of undesired hardware effects, enabling much greater ability to mitigate such effects. As of now, few results can be found in the scientific literature.

The project starts in the lab, where communication hardware is characterized, and the results are refined into theoretical expressions of maximum throughput with hardware constraints. From the theory we will derive multidimensional constellations, optimized for maximal throughput with given hardware constraints.

The project is an interdisciplinary cooperation between Prof. Thomas Eriksson (Dept. Signals& Systems), Assoc. Prof. Christian Fager (Dept. Microtechnology&Nanoscience), Prof. Erik Agrell (Dept. Signals&Systems) and Assoc. Prof. Tommy Svensson (Dept. Signals&Systems) at Chalmers, with a combination of expertise in signal processing for hardware constraints, efficient amplifier design, design of multidimensional constellations, and communication networks. Within the project period, the co-applicants will be active in different phases of the project, with Prof. Fager active in the early phases when lab measurements and hardware modeling techniques is needed, and Profs. Agrell and Svensson active in the later parts of the project when multi-dimensional constellations are designed and reworked into transmitter and receiver algorithms.

2. PURPOSE AND AIMS

Motivation: At companies, in standardization groups, and in overview research papers [1, 2], development and research on algorithms for dealing with imperfect communication hardware is recognized as extremely important for current and future communication generations. In wireless communication systems, non-ideal oscillators (with phase noise) and power amplifiers (nonlinear and low-efficient) have for a long time been recognized as the most important causes of hardware-related problems, both for single-antenna and multiple-antenna systems. It is also well known that modulation using sequences of independent complex-valued modulation symbols (such as QAM or PSK) is not an ideal form to handle such problems. In a typical communication system, a two-dimensional constellation (such as QAM and PSK) is used, together with a bandlimited pulse, to describe how the sinusoidal carrier is modulated. With a *multidimensional constellation* we mean

a constellation using more than the two dimensions used by traditional complex baseband modulation schemes, thereby, with a single symbol, describing the modulation at more than one frequency, time instant or antenna.

Below, we show several examples of processing techniques that are commonly used to mitigate problems originating from RF hardware inefficiency or imperfections.

Example 1: To avoid problems due to nonlinear amplifiers, Continuous Phase Modulation (CPM) and similar techniques have been used for a long time. CPM is a technique to introduce memory in the modulation, with the purpose of avoiding amplitude variations that are otherwise inevitable. The memory in CPM creates dependency between consecutive communication symbols, with the effect of implicitly creating a multidimensional constellation.

Example 2: With Orthogonal Frequency Division Multiplexing (OFDM), it is common to introduce peak-to-average-power-ratio (PAPR) reduction techniques (see Section 3), since high PAPR leads to very low amplifier efficiency. Such techniques introduce for example extra pilot subcarriers or phase rotations as a function of the transmitted data, in effect creating a multidimensional constellation.

Example 3: Phase noise is a stochastic process with memory, often modeled as a Wiener process [3]. Typically, the receiver implements a phase tracker (in single-carrier systems), or a common phase error (CPE) / intercarrier interference (ICI) removal algorithm (in OFDM) [4] followed by a standard detector/demodulator, or, if complexity restrictions allow it, joint phase noise tracking/detection [5]. All these techniques involve multiple consecutive modulation symbols, effectively implementing a multidimensional constellation, which of course is the natural way to handle any correlated noise.

Example 4: In multiple-antenna systems, it has been proposed to use constant-envelope modulation on each individual antenna [6], in order to avoid nonlinearity problems in the power amplifiers. The signal at the receiver is still designed to have amplitude variations by co-optimizing the signals to transmit at each antenna, in effect implicitly constructing a modulation space with M complex dimensions, where M is the number of transmit antennas.

Example 5: In multiple-antenna systems, cross-talk between antennas can lead to severe distortion of the RF signals at the antennas [7]. A suggested mitigation technique is multidimensional digital predistortion, where the input signal to each RF transmitter branch is created as a function of the desired output signals from all transmitter branches [8].

The techniques used in the above examples can be seen as workarounds or implicit ways to solve the basic problem; to deal with phase noise, amplifiers and cross-talk, one-dimensional complex constellations are not ideal. To strengthen this conclusion, we show in the section with preliminary results that the input distributions/modulation techniques achieving the highest possible throughputs for several channels with hardware-related issues are multidimensional.

Note that even for traditional additive white Gaussian noise (AWGN) channels, it has long been known that multidimensional symbols are beneficial; Shannon showed that for most cases, infinitely long blocks of symbols are needed to reach capacity. While this is true also for the hardware-impaired cases discussed here, the gains we are hoping to achieve by multidimensional coding are of an entirely different nature. The effects of hardware impairments are not possible to describe fully without a multidimensional description, which is quite different from an AWGN channel where noise is added independently for each symbol. Thus, the gains that we can hope to achieve are considerably larger, as is also illustrated in our preliminary work (section 6).

Relation to error-correcting codes: An error-correcting code is in itself a way to create a structured multidimensional constellation, and often it is the absolutely best technique, particularly when long capacity-achieving codes, such as turbo codes and LDPC (low-density parity check) codes, can be used. However, there are many reasons to study multidimensional constellations; we list some of the reasons below:

- The effects due to hardware impairments can be quite complicated to incorporate in a code, particularly in long codes such as LDPC. Instead, it may be a better approach to design a multidimensional constellation optimized for the impairments, and then apply a standard error-correcting code on top of the constellation.
- Even in systems where error-correcting coding is applied, many receiver algorithms, including clock recovery, equalization, and optical polarization tracking, utilize the *channel* bits as input to the feedback circuitry. The performance of the receiver thus depends on the *uncoded* system performance.
- In systems with extreme low-latency requirements, coding is not an option. This includes coordination of base stations in 4G cellular networks, feedback loops in control systems, high-end video conferencing and telepresence, and, as the most extreme example, automated stock-market trading, where even the speed of light is considered an obstacle.
- Low-cost systems use no or very limited DSP.
- In packet-oriented transmission, the data is preceded by a fixed preamble to mark the beginning of a packet. This preamble cannot be coded, since the received bit stream cannot be decoded at all unless it is first partitioned into blocks.
- The fundamental understanding of digital communication theory always begins with uncoded transmission, being the simplest, nontrivial case.

However, it is also true that error-correcting coding has been an important key to the success of wireless communication systems, and we believe that for a successful result, the constellations developed in this project should be able to coexist with a modern error-correcting code.

Goal: Our overall goals for this project are:

1) to develop expressions for the maximum achievable throughput for systems with a constraint on high amplifier efficiency, based on a thorough characterization of amplifiers
2) to develop expressions for the maximum achievable throughput for communication over a phase-noise limited channel, based on a thorough characterization of oscillators
3) to develop expressions for the maximum achievable throughput for transmitters with antenna mutual coupling, based on a thorough characterization of coupling effects
4) to find optimal, structured or unstructured, multidimensional constellations to operate power amplifiers efficiently, to overcome the negative effects of phase noise, and to handle antenna crosstalk, with a maintained high bit rate.

Thus, our goals will take us all the way from lab measurements, through theoretical results and basic communication theory, towards techniques to use in a practical communication link.

3. SURVEY OF THE FIELD

The area of the current proposal is to study *multidimensional constellations* for hardware-constrained communication, particularly related to efficient amplifiers, phase noise (wireless and optical), and MIMO transmitters.

COMMUNICATION WITH IMPERFECT HARDWARE

It is useful to study traditional techniques for compensation of hardware problems, to better understand how a multidimensional constellation can be used to improve the systems. Here we focus on the areas of *phase noise* and *nonlinear* and *efficient amplifiers*, which are considered as the most important hardware effects. Further, we study *mutually coupled antennas*, which is an increasingly important problem today.

Phase noise: In single-carrier systems, a typical receiver contains a pilot-based phase tracking device (a phase-locked loop or carrier recovery algorithm), sometimes enhanced by non-data aided or decision feedback techniques [9]. However, there will be remaining phase noise, and some authors report on joint phase noise tracking and detection [5]. There has been a few papers optimizing 2-D constellations for phase noise as well, based on the assumption of a well-tracked phase noise process [10, 11]. In our own work, we have derived theoretical bounds for phase noise tracking performance [12, 13], and joint estimation and detection schemes [14].

In OFDM systems, most receivers implement a common phase error (CPE) removal algorithm [15], sometimes followed by a procedure to remove the intercarrier interference (ICI) introduced by the phase noise [4]. We have ourselves proposed CPE/ICI removal schemes in [16, 17].

For phase noise in MIMO systems, the situation may be considerably worse, since some MIMO systems must have independent oscillators at each antenna[1], leading to not only phase rotation but also amplitude noise at the receiver, and in general a more difficult phase tracking problem. The literature focuses mostly on OFDM MIMO systems [18], while we have focused on single-carrier MIMO systems in [19-24].

Also in optical communication, random phase fluctuations is a dominant effect, both optical phase noise from the laser [25], and the Kerr nonlinearity in optical fibers. Similar techniques as used in wireless communication can also be used to combat optical phase fluctuations.

Nonlinear amplifiers: Much of the early literature on avoiding nonlinearity problems in single-carrier systems has been focused on constant-envelope techniques, e.g. CPM [26] or Gaussian minimum shift keying (GMSK) [27]. For OFDM, PAPR-reducing techniques dominates, such as selected mapping, active constellation extension, tone reservation, partial transmit sequences, etc. [28]; this is an area where we have been active [28, 29]. For MIMO systems, there is an interesting approach in [6], where the signal at each transmit antenna is chosen as a constant-envelope signal, calculated to give the desired (non-constant envelope) signal after combination at the receiver. This work is extended to account for amplifier efficiency in our paper [30].

While PAPR reduction and constant-envelope techniques may improve the power efficiency of an amplifier, there are very few papers that directly study how to choose signals for throughput maximization with high amplifier efficiency. Within this area, we have proposed various constrained envelope modulation schemes, e.g. [31] and evaluated the overall efficiency of such schemes in [32], and in [33] we derive the achievable throughput of an amplifier efficiency-limited communication link.

Mutually coupled antennas: Cross-talk between antennas, as an effect of mutual coupling between antennas, can lead to severe quality losses of the transmitted signals in a MIMO array [8]. The coupled signals lead to undesired load modulation of the amplifier, resulting in unpredictable RF output. In current systems, mutual coupling is avoided by the use of isolators at the amplifier

[1] The reason is that in some systems, the antennas are spaced too far apart to be possible to synchronize accurately.

outputs, but such isolators are bulky, costly and inefficient, and their use will be undesirable in upcoming small-cell systems (HetNet), or in massive MIMO systems, where each transmitter must be small and cheap. Thus, the output per branch in a coupled system is a function of the input of all branches, due to the antenna coupling. Some papers treating this topic are e.g. [8, 34], and we have ourselves studied the issue in [7, 35, 36].

In general, both the phase noise, amplifier and antenna coupling literature show what we discuss in Section 2: to handle phase noise and amplifiers, many consecutive samples must be treated in parallel, implicitly defining a multidimensional constellation. Below, we study more direct definitions of multidimensional constellations for this purpose.

MULTIDIMENSIONAL CONSTELLATIONS

By mapping points from a complex constellation to sinusoidal waveforms (modulation), the amplitude and phase of a bandlimited analog waveform can be arbitrarily controlled. It can be shown that such modulation is optimal in the case of a channel with additive white Gaussian noise (AWGN). While the optimality can be questioned in the case of hardware-induced distortion, the constellation-based description has large advantages and is very common, and we will in this proposal accept this framework and optimize it for imperfections due to hardware. A multi-dimensional constellation will in this framework give us much better control over the waveforms, enabling optimization to achieve goals in terms of lower distortion or better efficiency in the communication system.

In the literature, there have been many papers studying multidimensional constellations with a focus on AWGN or fading channels. Typically the constructions have been based on carving the signal sets from lattice codes [37], multistage approaches [38] or by using optimization techniques [39]. Some papers are focused on 4-dimensional constellations [40], which is an important special case due to the importance of polarization in optical channels channels [41]; we have ourselves contributed to this area in e.g. [42-45]. There are also work on higher dimensions [46]. Some of these works are also focused on MIMO channels, [47].

When we limit the literature search to multidimensional constellations for the purpose of handling undesired hardware effects, we find far less papers. In some papers, the authors show that multidimensional constellations can lead to a reduced PAPR compared to standard 2-D constellations [46, 48], with at least an indirect connection to amplifier efficiency. We are not aware of any multidimensional constellations optimizing performance in a wireless phase-noise limited channel, but for nonlinear optical fibers we have ourselves published a few papers [49]

Studying the literature in the relevant areas, our conclusion is that it is clear that there are obvious gains with studying `hardware-constrained communication in a multidimensional setting, but that very few authors did so explicitly.

4. PROJECT DESCRIPTION

The project is divided into two workpackages (WP:s), whereof the first is dedicated to theory for communication with phase noise, efficient amplifiers and MIMO transmitters with antenna mutual coupling, based on lab measurements. The second WP is related to the design of multidimensional constellations, both unstructured and structured, based on metrics and other results from WP1. The time plan for the two (partly overlapping) WP:s over the 4 years is outlined in the table below (green color is active). The co-applicants Christian Fager (CF), Erik Agrell (EA) and Tommy

Svensson (TS) are indicated; they are involved according to their expertise. The main applicant Thomas Eriksson and a PhD student are involved in all parts of the project (indicated by *).

The workpackages		Year 1	Year 2	Year 3	Year 4
WP1: Hardware analysis	Amplifiers	*,CF	*,CF		
	Phase noise	*,CF	*,CF		
	Antenna coupling	*,CF	*,CF		
WP2: Multidimensional constellations	Numerically		*, EA	*,EA,TS	
	Structured			*,EA,TS	*,EA,TS

WP1: THEORY FOR HARDWARE-CONSTRAINED COMMUNICATION

In this WP, we will aim to theoretically analyze and understand how hardware limits the performance of a communication link. The outputs from WP1 are performance metrics and probability distributions for various hardware effects, for use in the second WP.

- For **amplifier efficiency** and **amplifier nonlinearity**, the basis will be our work in [33] (see the preliminary work section below), where metrics for amplifier efficiency are developed, and the capacity-achieving distribution is derived for a amplifier efficiency-constrained SISO channel. This work will need to be extended towards a MIMO transmitter, describing the efficiency of the MIMO transmitter (including amplifiers, antennas etc) as a function of the chosen modulation. Efficiency measurements in the lab will be necessary to establish efficiency expressions for a general MIMO link. The output will be performance metrics and distributions, directly useful in WP2.
- For **phase noise**, we have developed bounds for the achievable rate for phase noise-limited communication in [50, 51] (for single-antenna channels), and there are also other theoretical works in the literature for this case that we can develop for our needs, e.g., [52]. For MIMO channels, there is little theory available in the literature. While fading channels have quite different properties than channels with phase noise, there are also similarities, and theory for fading channels can thus be a good starting point. Further, the theory that we have developed for the SISO case is also possible to develop further for MIMO. Again, a starting point is, as always, our lab.
- **Antenna mutual coupling** is a relatively new area of interest in the research literature. Our starting point will be the dual-input modeling of an amplifier with antenna cross-talk that we proposed in [7], deterministically describing the output generated by an M-antenna array by a set of two-input models. As opposed to previous research, we describe the far-field of the array, instead of the output from each antenna. This will enable construction of a multidimensional constellation (cross-antenna) creating the desired far-field in WP2.

We will be able to utilize previous and current work in other projects (e.g., the GHz Centre [53]) for the measurements and analysis in this WP.

WP2: MULTIDIMENSIONAL CONSTELLATIONS

In WP2, we will find optimal constellations based on metrics and results from WP1. The output is practical constellations for hardware-constrained communications, optimized for multiple simultaneous hardware imperfections.

- In the first stages of the project we will find optimal constellations by numerical optimization, much as was done for traditional 2-D constellations in e.g. [10] and by ourselves in [54], but extended to larger dimensionality. The criterion for optimization can be based on a cost metric, mutual-information, or based on a desirable probability distribution [54]. While unconstrained optimized constellations may be unpractical in some systems due to complexity, they may be useful in others, particularly if the dimensionality is kept low. Further, the performance of a numerically optimized constellation is always useful as a bound for the performance of constrained (structured) constellations.
- We will also study structured constellations, for complexity-reduced operation. We have previous experience with multi-ring constellations [55, 56] for 2D constellations, which can be extended to higher dimensionality. We also have worked with latttice- and sphere packings before [57, 58] which can be directly used, or transformed to optimize a metric by multidimensional companding techniques [59]. Some performance may be lost due to the structural limitations, but with the theory from WP1 and the numerically optimized results in WP2 we will have control over the losses, and the lower complexity makes structured constellations desirable in practice.

5. SIGNIFICANCE

In research and previous development of digital communication systems, it is clear that communication in the presence of hardware impairments is still a relatively uncharted territory, with many challenges left to solve. Those challenges cannot be ignored; with the hardware operating at its physical limits to catch up with the demands, imperfect hardware is more often than not the most significant limiting factor for the design of a high-throughput and power-efficient communication system, and in some cases even a show-stopper for the most demanding systems. This is even more prominent with upcoming techniques such as millimeter-wave communications and massive MIMO, where the hardware must be small and cheap.

Traditionally, the hardware-related problems are addressed by improving the hardware for existing communication signals, or by developing techniques to cope with the problems that are introduced by the hardware on traditional communication signals. Seldom the fundamentals of communication is expanded, and even more seldom people with algorithm and hardware competence work together to solve this problem. With the current proposal, we believe that hardware-constrained communication can be taken to the next level. Since we address the absolute fundamentals of communication systems, almost all communication applications can benefit from a successful project, and the impact can potentially be very large.

6. PRELIMINARY RESULTS

In this section, we present a few previously unpublished results that will have a large impact on the proposed project. Of course, we also have a lot of relevant results that are already published; these are presented in our publication lists and in Section 3.

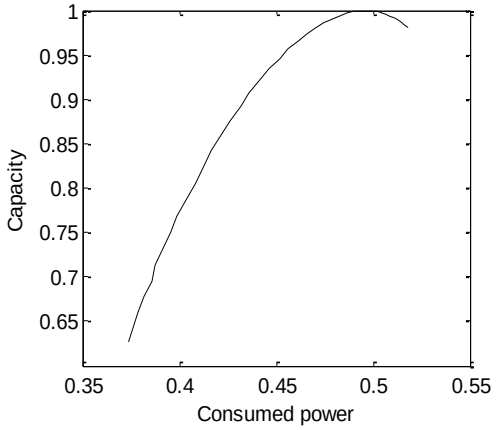
THE CAPACITY OF AN AMPLIFIER EFFICIENCY-LIMITED CHANNEL

In yet unpublished work, we have derived expressions for the capacity of a system where the amplifier efficiency must be maintained at a high level [33], with additional constraints on the

average output power and maximum amplitude. The optimal probability density function can be written as

$$f(\mathbf{x}) = ce^{-\lambda_1 P_{DC}(\mathbf{x}) - \lambda_2 \|\mathbf{x}\|^2 - P_{\max}(\mathbf{x})}$$

where $P_{\mathrm{DC}}(\mathbf{x})$ is the expression for the consumed power of the power amplifier, and $P_{\max}(\mathbf{x})$ is an expression to limit the maximum amplitude of the *analog* signal at the input of the power amplifier (to avoid clipping in the amplifier). Both $P_{\mathrm{DC}}(\mathbf{x})$ and $P_{\max}(\mathbf{x})$ are functions of the vector of consecutive complex baseband symbols $\mathbf{x} = \{x_n, x_{n-1}, ...\}$ (the expressions are given in [33]), which means that capacity is achieved by a multi-dimensional constellation. The coefficients λ_1 and λ_2 are used to control the consumed and output power of the system, respectively; by choosing λ_1 high, we will penalize consumed power and choose baseband symbols with low $P_{\mathrm{DC}}(\mathbf{x})$, while if we set λ_1 to 0 we will disregard consumed power.



In the figure, we illustrate the compromise between capacity and consumed power. For each point in the curve, the capacity-achieving pdf is multi-dimensional according to the equation above.

THE CAPACITY OF A PHASE-NOISE LIMITED CHANNEL

In a master's thesis by Johan Söder [51], we have made an analysis of the capacity of a channel with phase noise and AWGN, and this work has been continued in our paper [50]. In the paper we show that there are large gains by working with multi-dimensional pdfs and constellations. The derived approximate expression for the capacity-achieving pdf, limiting dependencies to two consecutive complex symbols x_n and x_{n-1}, is

$$f(x_n, x_{n-1}) = \alpha \frac{e^{-\beta\left(|x_n|^2 + |x_{n-1}|^2\right)}}{\sigma_\phi^2 + \frac{\sigma_w^2}{|x_n|^2} + \frac{\sigma_w^2}{|x_{n-1}|^2}} \quad \text{for } \angle x_n, \angle x_{n-1} \in (-\pi, \pi)$$

Here α and β are normalization constants, σ_ϕ^2 is the phase noise innovation variance and σ_w^2 is the AWGN variance. If we study the capacity-achieving pdf for 3 or more consecutive symbols, we get more complex expressions, but still possible to derive.

7. EQUIPMENT

The Microwave Electronics Lab at Chalmers is very well equipped for characterization of PAs and oscillators, as outlined below. No additional funding for instruments is needed.

Equipment	Specification	Relation to this project
Vector signal generator	Agilent E4438C	Generation of realistic modulated input signals for MIMO PA characterization.
Large signal vector network analyzer	MT4463A	Accurate two port black-box modeling of PAs and MIMO transmitter modules. To be used with VSG to emulate cross coupling effects.
High frequency oscilloscope	Agilent 54854A	Analysis of modulated output and input time domain waveforms.
Load-pull system	Maury Microwave	Characterization of PAs with tunable load impedance.

Vector network analyzer	Agilent PNA	Two-port, small signal characterization of MIMO antenna elements.
High performance digitizer	SP Devices ADQ214	High performance digitizer (A/D-converter) for high dynamic range characterization of sinusoidal or modulated signals. Can be used in measurement system for high dynamic range measurements.
Vector signal generator evaluation modules	Texas Instruments TSW3100EVM, DAC5682ZEVM	Very wideband vector signal generator. Provides additional inputs for MIMO transmitter testing.
Software defined radios	National Instrument USRP radios	Implementation of a 2x2 MIMO demonstrator

8. INTERNATIONAL AND NATIONAL COLLABORATION

For the project, our most relevant collaboration is within the VINNOVA-financed GHz Centre, where we cooperate with several Swedish and international companies (e.g. Ericsson, Saab, NXP etc.) on DSP-assisted hardware for communication. Our work in the GHz Centre will work as a practical and industry-oriented counterpart to the proposed project, and we will benefit considerably from this cooperation through the use of lab equipment for phase noise and amplifier measurements, and know-how of hardware constraints.

Other than GHz Centre, the applicants has formal and informal contacts with many leading institutions worldwide, participate in many projects funded by EU, SSF, VINNOVA etc.

9. OTHER GRANTS

Thomas Eriksson has an ongoing grant on “Modeling and signal design for multiple antenna architectures” (see the separate description), but this grant ends in Dec. 2015.

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Interdisciplinarity

My application is interdisciplinary

An interdisciplinary research project is defined in this call for proposals as a project that can not be completed without knowledge, methods, terminology, data and researchers from more than one of the Swedish Research Councils subject areas; Medicine and health, Natural and engineering sciences, Humanities and social sciences and Educational sciences. If your research project is interdisciplinary according to this definition, you indicate and explain this here.

Click here for more information

Scientific report

Scientific report/Account for scientific activities of previous project

Report on earlier approved VR project
"Modeling and signal design for multiple antenna architectures"

Project number: 621-2011-5820

Title: Modeling and signal design for multiple antenna architectures

Swedish Title: Modellering och signaloptimering för sändararkitekturer med flera antenner

Period: 2012-01-01 to 2015-12-31

Amount approved: 3 280 000 kr

Achieved scientific results up to now

My earlier VR project, on *modeling and signal design for multiple antenna architectures*, will conclude in Dec. 2015. In this project, we have worked with the design of signals in MIMO transmitters, to operate the transmitter as efficently as possible when hardware imperfections (such as imperfect amplifiers and oscillators) are limiting the performance. I also have money from a VINNOVA project on MIMO transmitters, the GHz Centre, which partly overlaps my VR project above but with a more hardware-oriented focus.

Our main results can be summarized as follows:

- We have developed a technique to model a power amplifier in a MIMO transmitter, including cross-talk between antennas, using a two-input model. One model input represents the input to the power amplifier, the other model input represents the reflected wave, from the antenna to the amplifier input, which is in contrast to earlier models that uses a combined model with M inputs and M outputs to represent the transmitter. Since complexity in identification and running the models grows exponentially with the size, this is a considerable complexity saving. More importantly, the technique enables characterization of MIMO transmitters operating only a single antenna branch of the transmitter, enabling characterization of the MIMO system using a SISO testbed. The results are documented in [1] [2].
- For the same MIMO transmitter with cross-talk, we have also developed techniques to linearize the entire transmitter using the same two-input modelling as above, with the same advantages. However, nothing is published yet (planned journal submission in May 2015).
- We have derived the optimal power allocation [3] and the capacity [4] for a MIMO transmitter with amplifier efficiency constraints. This lead to the somewhat surprising conclusion that antenna selection (choosing to transmit on only one antenna at the time per user) may be the best strategy for getting the maximal throughput for a given power consumption.
- In two practical papers we derived a Kalman-filter algorithm for joint estimation of channel parameters and phase noise in MIMO systems [5] [6], based on regularly transmitted pilots. This was later developed into an algorithm for joint phase estimation and detection in a MIMO system with phase noise [7].
- With massive MIMO, we have computed the performance when all antennas signal with low-peak-to-average signals, which when combined in the receivers still result in high-fidelity communication [8]. This work was done with a focus on amplifier power consumption.
- For massive MIMO transmitters, we have studied the effect of phase noise on the throughput using different precoding algorithms, [9]. This was done for three important settings; a) a single oscillator is used for the entire

antenna array, b) different oscillators are used for each antenna, or c) more than one oscillator is used, but there are less oscillators than the number of antennas; each oscillator drives a group of transmitters. Some conclusions are that it may be advantageous to use more than one oscillator if a matched filter precoder is used, but the resulting imperfect CSI results in an increased interuser interference, particularly with a zero-forcing precoder. A similar study was done in [10]. for OFDM transmission.

- In connection to working with MIMO transmitters with phase noise, we have computed the capacity for a massive MIMO downlink in [11].
- For massive MIMO, we analyzed several different hardware effects with respect to the perfromance penalty in [12]. In particular, we focused on the so called "averaging" effect that is promised for massive MIMO, and whether this effect is still present with hardware imperfections.

The relation to the planned project

In general, we have worked for a long time with hardware-constrained communication, and developed precoders and algorithms for modeling and compensation of such effects; in the soon finished VR project this was done in a MIMO transmitter setting. From this work, we have a thorogh understanding of the effects of imperfect hardware which will be utilized in the new proposed project. However, we have generally accepted whatever modulation that has been chosen, and worked with algorithms to compensate detremiental effects. In the new project we take our understanding one step further and develop new multidimensional constellations to entirely avoid the need to transmit hardware-unfriendly signals and instead optimize what we transmit to the given hardware.

Total resources available for the project

In addition to the VR project, I have had money from the VINNOVA-funded "GHz Centre" project [13], with a total budget to me of approximately 3.5 MSEK over the project time of 3 years. The GHz Centre project partly overlaps the VR project but with a more hardware-oriented focus, so I estimate that approximately 40%-50% of that project can be said to be available for research on signal optimization in MIMO (totally ~1.5 MSEK over the years). The GHz Centre project is performed in collaboration with 5 companies (Ericsson, SAAB, Infineon, NXP, National Instruments), so it can be seen as a practical/industry-oriented counterpart to the more theoretical VR project.

I also have money from a bilateral agreement with Ericsson (1 MSEK/year), but this project is unrelated to MIMO so the overlap is very small to none.

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[5] H. Mehrpoyan, et al., "Joint estimation of channel and oscillator phase noise in MIMO systems," IEEE Trans. Signal Processing, vol. 60, pp. 4790-4807, 2012.

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[10] R. Krishnan, et al., "On the Impact of Oscillator Phase Noise on the Uplink Performance in a Massive MIMO-OFDM System," IEEE Signal Processing Letters, 2015.

[11] M. R. Khanzadi, et al., "Capacity of Multiple-Antenna Phase-Noise Channels with Common/Separate Oscillators," accepted to IEEE Trans. Comm., 2015.

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Budget and research resources

Project staff

Describe the staff that will be working in the project and the salary that is applied for in the project budget. Enter the full amount, not in thousands SEK.

Participating researchers that accept an invitation to participate in the application will be displayed automatically under Dedicated time for this project. Note that it will take a few minutes before the information is updated, and that it might be necessary for the project leader to close and reopen the form.

Dedicated time for this project

	Role in the project	Name	Percent of full time
1	Applicant	Thomas Eriksson	20
2	Participating researcher	Christian Fager	5
3	Participating researcher	Erik Agrell	5
4	PhD Student	Doktorand NN	80
5	Participating researcher	Tommy Svensson	5

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	2019	Total
1	Applicant	Thomas Eriksson	20	252,000	261,000	270,000	280,000	1,063,000
2	PhD Student	NN	80	435,000	450,000	466,000	482,000	1,833,000
3	Participating researcher	Erik Agrell	5	66,000	68,000	71,000	73,000	278,000
4	Participating researcher	Tommy Svensson	5	50,000	52,000	54,000	56,000	212,000
5	Participating researcher	Christian Fager	5	49,000	50,000	52,000	54,000	205,000
	Total			852,000	881,000	913,000	945,000	3,591,000

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	Kontor	61,000	64,000	66,000	68,000	259,000
	Total	61,000	64,000	66,000	68,000	259,000

Running Costs

	Running Cost	Description	2016	2017	2018	2019	Total
1	Dator	Dator	30,000	0	0	30,000	60,000
2	Konfresor	Konfresor	30,000	30,000	30,000	30,000	120,000
3	Förbrukningsmaterial	Förbrukningsmaterial	10,000	10,000	10,000	10,000	40,000
4	IT-kostnader		19,000	19,000	20,000	21,000	79,000
	Total		89,000	59,000	60,000	91,000	299,000

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	852,000	881,000	913,000	945,000	3,591,000		3,591,000
Running costs	89,000	59,000	60,000	91,000	299,000		299,000
Depreciation costs					0		0
Premises	61,000	64,000	66,000	68,000	259,000		259,000
Subtotal	1,002,000	1,004,000	1,039,000	1,104,000	4,149,000	0	4,149,000
Indirect costs					0		0
Total project cost	1,002,000	1,004,000	1,039,000	1,104,000	4,149,000	0	4,149,000

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

Vi söker pengar för huvudsakligen 1 doktorand som jobbar till 80% i projektet (resten undervisning).
Huvudsökande söker 20% för handledning och projektledning.
De medsökande 5% för bihandledning i olika faser av projektet enligt tidplan.

En ny dator till doktoranden var 3:e år sökes.
1 konferensresa varje år för doktoranden.
Kontorskostnad, IT-kostnad, förbrukningsmaterial är kostnader för att upprätthålla en arbetsplats.

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

Appendix B: Curriculum Vitae Thomas Eriksson 640407-6116

1. Higher education

M.Sc. (Civilingenjör) in Electrical Engineering, Chalmers University of Technology, July 1990.

2. Doctoral degree

Ph.D. (Teknologie doktor) in Information Theory, Chalmers University of Technology, Nov. 6, 1996. Title: *Vector Quantization in Speech Coding*. Supervisor: Prof. Per Hedelin.

3. Post. Doc. positions

1997-1998 AT&T Research Labs, Florham Park, NJ, USA

1998-1999 KTH, Department of Speech, Music and Hearing, Stockholm

4. Docent

Sep 2006. Docent in Information Theory, Chalmers University of Technology.

5. Current employment

Feb 2011-current: Professor, Communication Systems, Department of Signals and Systems, Chalmers University of Technology. Main tasks are supervision of Ph.D. students, teaching (master and graduate courses) and research. I am also vice head of Signals&Systems, with responsibility for the undergraduate and master education. Currently ~40% research.

6. Previous employments

- July 1990--Dec. 1996: Ph.D. student and teaching assistant (doktorand), Department of Information Theory, Chalmers University of Technology.
- 1995, 1997, for Ericsson Microwave Systems in Mölndal, Göteborg. Giving courses in signal processing and speech coding.
- 1997--1998: Research consultant/PostDoc at AT\&T Research Labs, Florham Park, NJ, USA. Projects include development of speech coding algorithms at 1.2 kbps, speech synthesis and vector quantization.
- May 1998--May 1999: Working in a joint project between Ericsson Systems AB, Kista, and Department of Speech, Music and Hearing, Royal Institute of Technology (KTH). The main task was development of a speech coding algorithm at 4 kbps and supervision of PhD students.
- May 1999-2011: Associate Professor (universitetslektor/docent). Department of Signals and Systems, Chalmers University of Technology. Main tasks are supervision of Ph.D. students, teaching (master and graduate courses) and research.
- Sep 2003--Mar 2004: Guest professor. MCSP, Yonsei University, Seoul, S. Korea. Teaching and research on speaker recognition.

- Feb 2011-- : Professor (bitr. Professor), Department of Signals and Systems, Chalmers University of Technology. Main tasks are supervision of Ph.D. students, teaching (master and graduate courses) and research.
- Jan 2013-- : Full Professor, Department of Signals and Systems, Chalmers University of Technology. Main tasks are supervision of Ph.D. students, teaching (master and graduate courses) and research.

7. Interuptions in research

- On 100% parental leave from Jan. 2007 - Jun. 2007 (6 months)
- On 20% parental leave from Jan. 2008 - Apr. 2008 (4 months)

8. Supervision of Ph.D. students that have reached a PhD

- Ali Behravan (supervisor), Communication Systems Group, Dept. Signals and Systems, Chalmers University of Technology. Ph.D. May. 2006.
- Florent Munier (supervisor), Communication Systems Group, Dept. Signals and Systems, Chalmers University of Technology. Ph.D. May. 2007.
- Daniel Persson (main supervisor and examiner), Information Theory Group, Dept. Signals and Systems, Chalmers University of Technology. PhD. Jan. 2009.
- Guillermo Garcia (main supervisor and examiner), Communication Systems Group, Dept. Signals and Systems, Chalmers University of Technology. PhD. Dec. 2010.
- Ulf Gustavsson (main supervisor), Communication Systems Group, Dept. Signals and Systems, Chalmers University of Technology. PhD. Dec. 2011.
- Ali Soltani (main supervisor and examiner), Communication Systems Group, Dept. Signals and Systems, Chalmers University of Technology. PhD. Nov. 2012.
- Behrooz Makki (main supervisor and examiner), Communication Systems Group, Dept. Signals and Systems, Chalmers University of Technology. PhD. Dec. 2013.
- Rajet Krishnan (main supervisor and examiner), Communication Systems Group, Dept. Signals and Systems, Chalmers University of Technology. PhD. Apr. 2015.

9. Other Information

- Authored or co-authored 61 (56) published journal publications and 114 (77) conference papers (numbers inside parentheses are publications since 2007). Total number of citations: 2709. Updated information can be found on Google Scholar Citations, http://scholar.google.se/citations?hl=sv&user=fVYfscoAAAAJ
- Best paper at the *IEEE Workshop on Speech Coding*, USA, 2001 for the paper ``An information theoretic perspective on the speech spectrum process," by F. Norden, T. Eriksson and P. Hedelin.
- Best paper at *NORSIG*, Helsinki, Finland, 1996 for the paper ``Improving predictive vector quantizers in speech coding applications.," by J. Lindén, J. Skoglund and T. Eriksson.
- Applicant or co-applicant to 11 funded research grants, 2003-2013.
- Supervision of 15 PhD students totally, whereof as of now 7 has reached a PhD.
- Vice head at Signals&System, with responsibility for education.

Christian Fager

Date of birth: 1974-11-30
Address: Dept. Microtechnology and Nanoscience,
Chalmers University of Technology, SE-41296, Göteborg, Sweden
Contact: Tel. +46 (31) 772 5047, email: christian.fager@chalmers.se

1. Higher education qualification

1998-05-01 **Electrical Engineering**, Chalmers, Sweden

2. Doctoral degree

2003-06-13 **PhD thesis** "Microwave FET Modeling and Applications", Chalmers, Sweden

3. Postdoctoral positions

2014/07–14/08: **Visiting Scholar**, University of California San Diego (UCSD), USA
2003/06–04/12: **Postdoctoral Researcher**, Microwave Electronics Laboratory, Chalmers

4. Qualification required for appointment as a docent

2010-02-01 **Docent Diploma** (Associate Professor competence)

5. Current position

2011/04– **Associate Professor (docent)**, Microwave Electronics Laboratory, Chalmers.

6. Previous positions and periods of appointment

2009/01–11/03: **Project leader,** Microwave Electronics Laboratory, Chalmers.
2005/01–08/12: **Assistant professor,** Microwave Electronics Laboratory, Chalmers
2003/06–04/12: **Postdoctoral Researcher**, Microwave Electronics Laboratory, Chalmers
1998–2003: **Ph.D. student, M**icrowave Electronics Laboratory, Chalmers

7. Interruption in research

2014/09 – 14/12 **Parental leave**, 80%
2011/01 – 11/08 **Parental leave**, (2011/01 – 11/03: 50%, 2011/04 – 11/08: 100%)

8. Supervision

- **Main supervisor for 5 PhDs:** D. Gustafsson (Oct. 2014), M. Özen (May. 2014), P. Saad (Nov. 2012), H. Cao (Dec. 2011), H. Nemati (Dec. 2010).
- **Co-supervisor for 4 PhDs**: C. Andersson (May 2013), A. Soltani (Dec. 2012), U. Gustavsson (Dec. 2011), K. Andersson (Nov. 2006)
- **Presently main-/co-supervisor for 3/2 PhDs.**
- **Main/co supervisor for 1/1 post-doc.**

9. Other information of relevance to the application

9.1. Publication statistics

h-index: 20. (Google Scholar, 2015-03-27). Authored or co-authored 38 peer-reviewed international journal publications and 70 international conference papers. Total citations: 1565. Complete publication list: http://scholar.google.se/citations?user=57OMjKQAAAAJ

9.2. International collaborations

- **PhD student exchanges (>3 months):** Univ. Aveiro (Portugal), Univ. Cantabria (Spain), Univ. Torino (Italy), Cardiff Univ. (U.K.), TU Delft (The Netherlands), Univ. Rome Tor Vergata (Italy), POSTECH (S. Korea), Southeastern University (China)
- **Other Academic Collaborations with Joint Papers:** KU Leuven (Belgium), Univ. College Dublin (Ireland), Univ. Warzaw (Poland), Univ. Padova (Italy), Vrije Univ. Brussels (Belgium)
- **Responsible for Chalmers in EU Network of Excellence (2004-2007): TARGET** (Top Amplifier Research Groups in a European Team). 47 organizations, 240 researchers

9.3. Prizes, Awards, and special grants

- **Ericsson Research Foundation Grant**, support for research stay at UCSD (2014)
- **Best Paper Award**, IEEE Wireless and Microw. Techn. Conf., USA (2011)
- **Outstanding Reviewer Award**, IEEE Microw. Wireless Comp. Lett. (2011)
- **Area-of-Advance Award,** Chalmers University of Technology, Sweden (2010)
- **Best (student) Paper Award**, IEEE International Microwave Symp., Seattle, U.S.A. (2002)

9.4. Commissions of trust, Organization of Scientific Meetings, etc.

- **Associate Editor**, *IEEE Microwave Magazine*, 2015-
- **General Chairman**, *Swedish Microw. Days/GigaHertz Symposium*, 2014, Chalmers,(~250p)
- **Conference Co-Organizer**, *Int. Workshop on Integrated Nonlinear Microwave and Millimetre-wave Circuits (INMMiC)*, Göteborg, Sweden, 2010. (~80 participants)
- **Workshop Co-organizer**, *IEEE International Microwave Symp*., Boston, USA, 2009.
- **Invited Panel Session Member**, "5G Power Amplifier Technologies," (invited experts from NXP, Qorvo, Skyworks, Huawei, UCSD) *IEEE Radio Wireless Week*, 2015
- **Technical Review Committee Sub-committee Chair/Vice Chair/Member**: *IEEE International Microwave Symposium, 2012-*
- **Steering Board Member**, *IEEE International Microwave Workshop Series on "RF Front-ends for Software Defined and Cognitive Radio Solutions*," Portugal, 2010.
- **Editorial Board Member** for *Int. J. of RF and Microwave CAE (2009-2014)*
- **Program Committee Member**: *International Workshop on Integrated Nonlinear Microwave and Millimetre-wave Circuits (INMMiC)* and *GigaHertz Symposium.*
- **Invited External Examiner** for 3 intl. PhDs (Norway, Ireland, Canada) and 2 Lic. theses.
- **Invited PhD Evaluation Committee Member** for 6 PhD defenses.
- **Founder and Organizer of new Student Design Competition at Intl. Microwave Symp.**: "*Digital Pre-Distortion of Power Amplifiers*", (www.dpdcompetition.com), 2014-
- **Research Proposal Reviewer** for *Technology Foundation STW*, the Netherlands
- **Frequent Reviewer** for *IEEE Trans. Microw. Theory Tech., IEEE Microw. Wireless Comp. Lett., Int. J. RF and Microw. Computer-Aided Eng., IEE Elec. Lett., Int. Microw. Symp., European Microw. Conf., Intl. Nonlinear Microwave and Millimetre-wave Circuits Conf.*

9.5. Invited workshop presentations

- **IEEE Radio Wireless Week**, USA: Jan 2008, Jan 2014, Jan 2015
- **International Microwave Symposium**, USA: June 2009, June 2011, June 2014 (2×)
- **International Wireless Symposium**, China: April 2013
- **European Microwave Week**, Sept. 2006, Oct. 2007 (2×), Oct. 2009
- **National Instruments Week**, USA, Aug. 2014

9.6. Project leadership

Since 2005 leader and technically responsible for five collaboration projects in the area of energy efficient transmitters for wireless communications. Partners: Ericsson, SAAB, Infineon, NXP Semiconductors, ComHeat Microwave. Total cash budget managed: >3M€.

9.7. Other

PhD students under my supervision have been awarded: IEEE Graduate Fellowship Award (2013), PhD Student Fellowship for EuMIC 2012, 2 × Best (Student) Paper Award Finalist at IEEE IMS (2013, 2015), Student High Efficiency Power Amplifier Design Competition Winner (2011), Outstanding Achievement Awards (2008, 2010). Scholarship for Excellent Chinese Oversea PhD Students (2011). Ericsson Research Foundation Scholarship (2010).

Curriculum Vitae—Erik Agrell

1 Higher education degree

- Master of Science in Electrical Engineering, Chalmers University of Technology, 1989.

2 Doctoral degree

- Doctor of Philosophy in Information Theory, Chalmers, 1997. Dissertation title: "Voronoi-based coding." Supervisor: Prof. Per Hedelin.

3 Postdoctoral positions

- Coordinated Science Laboratory, University of Illinois at Urbana-Champaign (UIUC), 1997–1998 (half time).
- Center for Wireless Communication, University of California, San Diego (UCSD), 1997–1998 (half time), 1998–1999 (full time).

4 Qualifications required for appointment as a docent

- Docent in Communication Systems, Chalmers, 2003.

5 Current position

- Professor in Communication Systems at the Department of Signals and Systems, Chalmers, since 2009. Full Professor since 2013. About 75% research in 2015.
- Visiting Professor at University College London, U.K., since 2014. Honorory position corresponding to about 10 % of full time.

6 Previous positions and periods of appointment

- 2001–2009, Associate Professor, Department of Signals and Systems, Chalmers.
- 1999–2001, Associate Professor, Department of Electrical and Computer Engineering, Chalmers Lindholmen University College, Göteborg.
- 1990–1997, Research Assistant, Department of Information Theory, Chalmers.
- 1988–1990, Systems Analyst, AB Volvo, Technical Development, Göteborg.

7 Interruption in research

- 2005–2008, part-time parental leave and leave of absence, 6 months full-time equivalent.
- 1993–1997, part-time parental leave and sick leave, 11 months full-time equivalent.

8 Supervision

- Ph.D. students: Christian Häger, licentiate 2014, cosupervisor; Tobias Eriksson, licentiate 2014, cosupervisor; Naga V. Irukulapati, licentiate 2014, cosupervisor; Mikhail Ivanov, licentiate 2013, cosupervisor; Krzysztof Szczerba, Ph.D. 2013, cosupervisor; Kasra Haghighi, Ph.D. 2013, cosupervisor; Johnny Karout, Ph.D. 2013, main supervisor; Lotfollah Beygi, Ph.D. 2013, main supervisor; Martin Sjödin, Ph.D. 2012, cosupervisor; Alex Alvarado, Ph.D. 2011, cosupervisor; Hongxia Zhao, Ph.D. 2008, main supervisor; Matts-Ola Wessman, licentiate 2005, cosupervisor; and Johan Lassing, Ph.D. 2005, cosupervisor.
- Postdoctoral researchers: Juzi Zhao, postdoc 2014–present; Debarati Sen, postdoc 2011–2012; A. Serdar Tan, postdoc 2009–2010; and Torsten Wuth, postdoc 2004.

9 Other information of relevance to the application

9.1 Distinctions

- Best poster award, 2013 IEEE Communication Theory Workshop (CTW).
- 2013 Supervisor of the Year, Chalmers University of Technology.
- Best paper award, 2011 IEEE Global Communications Conference (GlobeCom).
- Best poster award, 2009 IEEE Information Theory Workshop (ITW).
- The 1990 John Ericsson medal for "outstanding scholarship for the degree of Master of Science in Engineering."

9.2 Research grants (selected)

- P. Andrekson, M. Karlsson, V. Torres Company, and E. Agrell, "Technologies for spatial-division multiplexing: The next frontier in optical communications," 2015–2018, VR framework grant no. 2014-6138, 12000 kSEK.
- L. Wosinska, J. Chen, E. Agrell, and R. Forchheimer, "Towards flexible and energy-efficient datacentre networks," 2015–2018, VR framework grant no. 2014-6230, 9000 kSEK.
- E. Agrell, G. Durisi, and M. Karlsson, "Optical fiber interference is not noise," 2014–2017, VR no. 2013-5271, 4720 kSEK.
- P. Andrekson, A. Larsson, M. Karlsson, E. Agrell, and P. Larsson-Edefors, "Energy-efficient optical fibre communication," 2014–2018, Knut och Alice Wallenbergs Stiftelse no. 2013.0021, 33894 kSEK.
- E. Agrell, H. Wymeersch, P. Andrekson, and M. Karlsson, "Adaptive optical networks: Theory and algorithms for system optimization," 2013–2016, VR framework grant no. 2012-5280, 12000 kSEK.
- F. Brännström, A. Alvarado, and E. Agrell, "MIMO-BICM: Fundamentals, analysis, and design", 2012–2015, VR no. 2011-5950, 3280 kSEK.
- E. Agrell and M. Karlsson, "Theory and algorithms for fiber-optical intensity channels", 2011–2013, VR no. 2010-5757, 2400 kSEK.
- P. Andrekson, M. Karlsson, E. Agrell, H. Wymeersch, and G.-W. Lu, "Power-efficient terabit/s transmission," 2011–2014, VR framework grant no. 2010-4236, 9600 kSEK.
- P. Andrekson, M. Karlsson, and E. Agrell, "Next generation optical communication systems," 2008–2013, SSF framework grant no. RE07-0026, 20800 kSEK.
- M. Karlsson, P. Andrekson, and E. Agrell, "Advanced optical communication technologies for access and transport networks," 2008–2011, Vinnova no. 2007-02930, 9000 kSEK.
- E. Agrell and M. Karlsson, "Coded modulation for band-limited optical channels," 2008–2010, VR no. 2007-6223, 2250 kSEK.

9.3 Outreach and research community services (selected)

- Invited papers in, e.g., Phil. Trans. Royal Society A 2015, IEEE/OSA J. Lightwave Technol. 2015, Proc. Tyrrhenian Int. Workshop on Dig. Commun. 2015, Proc. OECC 2015, Proc. IEEE SPAWC 2015, Proc. ITW 2015, Proc. OFC 2015, IEEE/OSA J. Lightwave Technol. 2014, Proc. ECOC 2013, Proc. 2013 OFC, Proc. 2012 IEEE IPC, Proc. ITA 2012, Proc. OFC 2012, Proc. IEEE Photonics Soc. Ann. Meeting 2010, Proc. ECOC 2010, and Proc. IWCMC 2009.
- Invited book chapters in *Enabling Technologies for High Spectral-Efficiency Coherent Optical Communication Networks,* Wiley, 2015; *Impact of Nonlinearities on Fiber Optic Communication,* Springer, 2011; and *Experimental Design for Combinatorial and High Throughput Materials Development,* Wiley, 2003.
- TPC member of OFC 2015, ICC 2015, Tyrrhenian Int. Workshop on Dig. Commun. 2015, and GlobeCom 2105.
- Technical Program Co-Chair of the 7th International Symposium on Turbo Codes and Iterative Information Processing, Göteborg, Aug. 2012.
- Associate Editor for *IEEE Transactions on Communications*, 2012–present.
- Publications Editor of *IEEE Transactions on Information Theory*, 1999–2002.
- Cofounder of Fibre-Optic Communications Research Centre (FORCE) at Chalmers, 2010 (chalmers.se/force). The center, currently involving about 35 researchers, originates in interdisciplinary collaboration initiated by E. Agrell and M. Karlsson in 2003.

CV for Tommy Svensson (http://www.chalmers.se/en/staff/Pages/tommy-svensson.aspx)

Tommy Svensson is Associate Professor in Communication Systems at Chalmers University of Technology ("Chalmers"), Gothenburg, Sweden, where he is leading the research on air interface and microwave backhauling network technologies for future wireless systems.

His main expertise is in design and analysis of physical layer algorithms, multiple access schemes, coordinated multipoint schemes, as well as moving relays/cells/networks for wireless access and wireless backhaul networks, and recently satellite networks. He also has industrial experience of higher layers and system design for wireless communication systems. He has co-authored two books and more than 110 journal and conference papers. IEEE Senior member.

1. Higher education qualification(s):

MSc ("Civilingenjör"), Engineering Physics, Chalmers, Dec 1994.

2. Doctoral degree

Ph.D. in Information Theory from Chalmers, March 2003. Ph.D. Thesis defended Jan 2003, "Spectrally Efficient Continuous Phase Modulation". Thesis supervisor: Arne Svensson, Chalmers.

3. Postdoctoral positions

- Coordinator Chalmers Master Program on Communication Engineering Jan. 2012-present.
- Own research and coordinator of Chalmers involvement together with Third party Uppsala University in the EU FP7 METIS project https://www.metis2020.com, and EU FP7 ARTIST4G project https://ict-artist4g.eu.
- Own research and coordinator of Chalmers involvement in the emerging EU Horizon2020 5GPPP mmMAGIC project focusing on mmWave for access and backhauling, starting mid 2015.
- Initiator, project leader and own research within the VINNOVA project on Microwave backhauling for IMT advanced and beyond (MAGIC).
- Project preparation and project leading of "Mobility management, control and routing technology for IMT-Advanced and beyond" project with Beijing University of Post and Telecommunications (BUPT) within the VINNOVA-MOST (Ministry of Science and Technology in China) program on IMT Advanced and Beyond.
- Coordination with budget, legal contracts, cost claims, reporting and work planning responsibilities, for Chalmers and our Third parties Uppsala and Karlstad university in the EU FP6 IST-2003-507581 WINNER (2004-2005), IST-4-027756 WINNER II (2006-2007) and CELTIC CP5-035 WINNER+ projects. http://projects.celtic-initiative.org/winner+/
- Own research within the WINNER, WINNER II and WINNER+ projects. In WINNER II also task leader of the multiple access task with extensive contributions to the WINNER II system concept. The WINNER projects have been acknowledged by the EU commission: http://europa.eu/rapid/pressReleasesAction.do?reference=IP/09/1238
- Attracted external funding from VINNOVA, ESA, EU and VR accumulated until present to 40 MSEK.
- Reviewer of conference papers and journal papers such as IEEE Globecom, VTC, ICC, PIMRC, IEEE WCNC, Milcom, and COST289; IEEE Trans. Wireless Comm., Communications, Communications Letters, Wireless Communications Letters, Journal on Selected Areas in Communications, Trans. Vehicular Technology, Proc. of the IEEE, Wireless Communications Magazine, EURASIP Journal on Wireless Communications and Networking, Wiley Wireless Communications and Mobile Computing, China Communications, IET Communications
- TPC member: EUSIPCO 2011/2012, EW2011, VTC2012-Fall/2013Spring, ISWCS2010, PIMRC2010/2012/2014, WEMIC 2006, ICC2014, WCNC2013/2014, Globecom BWA workshop 2013, SweCTW2011/2012/2013, ICCVE2013/2014, ICC2014/2015, 5GU2014
- Workshop steering committee member of SweCTW 2011, 2012, 2013, 2014.
- Organizing committee member at SNOW workshop 2014, Åre, Sweden.
- Tutorial on "Coordinated Multi-Point in Cellular Networks" at ICC'2013, June 2013, Budapest, Hungary, SweCTW'2013, Aug 2013, Gothenburg, Sweden, ISWCS'2013, Aug 2013, Ilmenau, Germany.
- Track chair VTC2013-Spring, Track co-chair VTC2012-Spring.
- Research Evaluator for Research Council of Norway, 2004, Italian Research and University Evaluation Agency, ANVUR&PRIN, 2013, Cyprus Research Promotion Foundation 2014.

- Co-organizer of "International Workshop on Emerging Technologies for LTE-Advanced and Beyond-4G" 2012, in conjunction with IEEE Globecom 2012, 2013, 2014 and 2015(to appear).
- Evaluation committee member of PhD candidates Daniel Calabuig Soler, Universidad Politécnica de Valencia (UPV), Dec 2009; Emil Björnsson, KTH Nov 2011; Tania Villa Trapala, EURECOM, France, Sep 2013; pre-eval&opponent Xiaojia Lu, Oulu University, Finland, Sep.&Dec. 2013; Johannes Lindblom, Linköping University, Sweden, Jan 2014; Sara Modarres Razavi, LiU Norrköping campus, May 2014; Lei Shi, KTH, June 2014; Miltiades FILIPPOU, EURECOM, July 2014; Hamed Farhadi, KTH, Dec 2014.
- Invited speaker at the WWI Innovation Day, Brussels, Nov 2007, European Commission FP7 Consultation Meeting: Future Mobile and Wireless Radio Systems, Feb 6, 2008.
- Technical Reviewer of 4 STREP project in EU FP7 and FP6 within Information and Communication Technologies (ICT), Objective ”The Network of the Future”, 2009 and 2010.
- Invited as Horizon2020 project applications evaluator.
- Expert member of EU H2020 5GPP-related Networld2020 European Technology Platform (ETP).
- Development and teaching of the ESS165/ESS166 Communication Systems course in the undergraduate Electrical Engineering program E3 during 2003, 2004, 2005 and 2007.
- Guest lecturer in Communication Engineering Master Program course SSY135 Wireless communications, 2009, and SSY145 Wireless Networks, 2009-2014, Beijing University of Posts and Telecommunications (BUPT), Beijing, China, 2010.
- June 2006 - Aug 2007: Board member, Sep 2007 - Dec 2009: Vice Chairman, and Jan 2010 to Present: Chairman of IEEE Sweden VT/COM/IT Chapter. Received the IEEE Comsoc Chapter Achievement Award 2011, 2012 and 2013, and IEEE Information Theory Society Chapter of the Year Award 2013, as well as the IEEE Comsoc Special recognition award "For long-time achievements in chapter activities and ongoing excellence serving its members", 2013.
- Best paper award at IEEE International Conference on Connected Vehicles & Expo (ICCVE’2013), Las Vegas, USA, Dec 2013.

4. Qualification required for appointment as a docent

June 23, 2010, at Chalmers. Docent seminar: “Research Towards IMT Advanced and Beyond”.

5. Present position, period of appointment

- 2010/07, Present, Chalmers, Associate Professor. Time for research in the position: about 40%.

6. Previous positions and periods of appointment

2008/01-2010/07, Chalmers, Project Manager & Project applications and coordination, Research towards Associate Professor competence. **2004/01-2008/01**, Chalmers, Assistant Professor, Research, teaching and project management. **2003/02-2004/01**, Ericsson AB, Mölndal, System Designer, System design of Point-to-point Microwave Radio Links. Then, leave of absence until 2005-12-31. **2003/01-2003/05**, Chalmers, Lecturer. **1997/09-2003/01**, Chalmers and part time employment at Ericsson Microwave Systems AB, Mölndal, Ph.D. student, Ph.D. studies on coded modulation. **1994/12-1997/08**, Ericsson Mobile Data Design AB, Gothenburg, Software Engineer and System Designer, project leader, design and implementation of software systems for mobile packet data switches in Mobitex, PPDC and GPRS.

7. Deductible time

2003/02-2004/01 Ericsson AB, Mölndal, Sweden, System Designer, Ericsson MINI-LINK.

8. Supervision

- Main supervisor of 3 PhD students, Jingya Li, Yutao Sui and Tilak Rajesh Lakshmana. All three obtained their Licentiate degrees in early 2013. The defense of Jingya Li is scheduled for April 29, 2015, and the other two are expected to graduate their PhD during autumn 2015.
- I am/have been co-supervisor of 6 PhD students, whereof Nima Jamaly and Behrooz Makki defended their PhD thesis April and Nov. resp. 2013, Wei Wang defended her Licentiate degree Jan. 2006. Currently I’m co-supervising 3 PhD students, Rajet Krishnan, Rahul Devassy, and Srikar Muppirisetty. Srikar defended his Licentiate Dec. 2014, and Rajet will defend his PhD April 10, 2015.
- Postdoctoral researchers under my guidance: Carmen Botella Mascarell Jan 2009-Jan 2011; Hani Mehrpouyan Sep 2010 - April 2012; Agisilaos Papadogiannis Aug 2011 - Feb 2013. Nima Seifi April 2013-Sep 2013. Behrooz Makki Nov 2013 - present.
- Supervision of external/internal MSc theses, leading to several conference and journal publications.

Publication list

Thomas Eriksson: Publications 2007-2015

1. PUBLICATION STATISTICS

Citations

Citation data is from March, 2015. (Google Scholar)
Look at http://scholar.google.se/citations?user=fVYfscoAAAAJ&hl=en for an updated Google Scholar overview of my papers and citations, H-index etc.

5 most cited articles

[1] E. Agrell, T. Eriksson, A. Vardy, and K. Zeger, "Closest point search in lattices," IEEE Transactions on Information Theory, vol. 48, pp. 2201-2214, Aug. 2002.
No citations: 1169

[2] T. Eriksson and T. Ottosson, "Compression of feedback for adaptive transmission and scheduling," IEEE Proceedings, vol. 95, pp. 2314-2321, Dec. 2007.
No citations: 75

[3] T. Eriksson, J. Lindén, and J. Skoglund, "Interframe LSF quantization for noisy channels," IEEE Transactions on Speech and Audio Processing, vol. 7, pp. 495-509, September 1999.
No citations: 67

[4] A. Soltani, H. Cao, S. Afsardoost, T. Eriksson, M. Isaksson, and C. Fager, "A Comparative Analysis of the Complexity/Accuracy Tradeoff in Power Amplifier Behavioral Models," IEEE Transactions on Microwave Theory and Techniques, vol. 58, pp. 1510-1520, June 2010.
No citations: 62

[5] P. S. Kildal, A. Hussain, X. Chen, C. Orlenius, A. Skårbratt, J. Åsberg, T. Svensson, and T. Eriksson, "Threshold Receiver Model for Throughput of Wireless Devices with MIMO and Frequency Diversity Measured in Reverberation Chamber," IEEE Antennas and Wireless Propagation Letters, 2011.
No citations: 47

2. PEER-REVIEWED JOURNAL ARTICLES 2007-2015

[1] B. Makki, T. Svensson, T. Eriksson, and M. Debbah, "On Feedback Resource Allocation in Multiple-Input-Single-Output Systems using Partial CSI Feedback," *IEEE Transactions on Communications,* 2015.
No citations: 0

[2] P. Landin, S. Gustafsson, C. Fager, and T. Eriksson, "WebLab: A Web-Based Setup for PA Digital Predistortion and Characterization," *IEEE Microwave Magazine,* vol. 16, pp. 138-140, 2015.
No citations: 0

[3] R. Krishnan, M. R. Khanzadi, A. Graell i Amat, T. Eriksson, and R. Schober, "Linear Precoding in the Presence of Phase Noise in Massive MIMO Systems -

A Large-Scale Analysis," *accepted to IEEE Transactions on Vehicular Technology,* 2015.
No citations: 0
[4] R. Krishnan, G. Colavolpe, A. Graell i Amat, and T. Eriksson, "Algorithms for Joint Phase Estimation and Detection for MIMO systems in the presence of Phase Noise," *accepted to IEEE Transactions on Signal Processing,* 2015.
No citations: 0
[5] M. R. Khanzadi, G. Durisi, and T. Eriksson, "Capacity of Multiple-Antenna Phase-Noise Channels with Common/Separate Oscillators," *accepted to IEEE Transactions on Communications,* 2015.
No citations: 2
[6]* D. Persson, T. Eriksson, and E. G. Larsson, "Amplifier-Aware Multiple-Input Single-Output Capacity," *IEEE Transactions on Communications,* pp. 1-7, 2014.
No citations: 2
[7] B. Makki, T. Svensson, T. Eriksson, and M.-S. Alouini, "Adaptive Space-Time Coding using ARQ," *IEEE Transactions on Vehicular Technology,* 2014.
No citations: 0
[8] B. Makki, A. Graell i Amat, and T. Eriksson, "Green Communication via Power-optimized HARQ Protocols," *IEEE Transactions on Vehicular Technology,* vol. 63, pp. 161-177, 2014.
No citations: 8
[9] B. Makki, A. Graell i Amat, and T. Eriksson, "On Noisy ARQ in Block-Fading Channels," *IEEE Transactions on Vehicular Technology,* vol. 63, pp. 731-746, 2014.
No citations: 5
[10] B. Makki, T. Eriksson, M. S. Alouini, and T. Svensson, "Coordinated Hybrid Automatic Repeat Request," *IEEE Communications Letters,* 2014.
No citations: 3
[11] B. Makki and T. Eriksson, "On the Performance of MIMO-ARQ Systems with Channel State Information at the Receiver," *IEEE Transactions on Communications,* pp. 1-16, 2014.
No citations: 6
[12] M. R. Khanzadi, D. Kuylenstierna, T. Eriksson, and H. Zirath, "Calculation of the Performance of Communication Systems from Measured Oscillator Phase Noise," *IEEE Transactions on Circuits and Systems,* pp. 1-13, 2014.
No citations: 8
[13] D. Persson, T. Eriksson, and E. G. Larsson, "Amplifier-Aware Multiple-Input Multiple-Output Power Allocation," *IEEE Communications Letters,* vol. 17, pp. 1112-1115, May 2013.
No citations: 7
[14] B. Makki, T. Eriksson, and T. Svensson, "On an HARQ-based Coordinated Multi-point Network using Dynamic Point Selection," *EURASIP Journal on Wireless Communications and Networking,* 2013.
No citations: 3
[15] B. Makki and T. Eriksson, "Feedback Subsampling in Temporally-Correlated Slowly-Fading Channels using Quantized CSI," *IEEE Transactions on Communications,* 2013.
No citations: 5
[16] B. Makki and T. Eriksson, "Fairness, Power Allocation, and CSI Quantization in Block Fading Multiuser Systems," *EURASIP Journal on Wireless Communications and Networking,* 2013.
No citations: 1

[17]* R. Krishnan, M. R. Khanzadi, T. Eriksson, and T. Svensson, "Soft metrics and their Performance Analysis for Optimal Data Detection in the Presence of Strong Oscillator Phase Noise," *IEEE Transactions on Communications,* 2013.
No citations: 8
[18]* R. Krishnan, A. Graell i Amat, T. Eriksson, and G. Colavolpe, "Constellation optimization in the presence of strong phase noise," *IEEE Transactions on Communications,* 2013.
No citations: 2
[19] M. R. Khanzadi, R. Krishnan, and T. Eriksson, "Estimation of Phase Noise in Oscillators with Colored Noise Sources," *IEEE Communications Letters,* vol. 17, pp. 2160-2163, 2013.
No citations: 5
[20] H. Mehrpoyan, A. A. Nasir, S. D. Blostein, T. Eriksson, G. K. Karagiannidis, and T. Svensson, "Joint estimation of channel and oscillator phase noise in MIMO systems," *IEEE Transactions on Signal Processing,* vol. 60, pp. 4790-4807, 2012.
No citations: 44
[21] B. Makki, N. Seifi, and T. Eriksson, "Multi-user Diversity with Two-Step channel state information feedback," *IET Communications,* vol. 6, pp. 1119-1125, 2012.
No citations: 3
[22] B. Makki, A. Graell i Amat, and T. Eriksson, "HARQ Feedback in Spectrum Sharing Networks," *IEEE Communications Letters,* vol. 16, pp. 1337-1340, 2012.
No citations: 9
[23] B. Makki, A. Graell i Amat, and T. Eriksson, "On ARQ-based Fast-Fading Channels," *IEEE Communications Letters,* vol. 16, pp. 1921-1924, 2012.
No citations: 2
[24] B. Makki and T. Eriksson, "On Hybrid ARQ and Quantized CSI Feedback Schemes in Quasi-Static Fading Channels," *IEEE Transactions on Communications,* vol. 60, pp. 986-997, 2012.
No citations: 22
[25] B. Makki and T. Eriksson, "On the average rate of HARQ-based quasi-static spectrum sharing networks," *IEEE Transactions on Wireless Communications,* vol. 11, pp. 65-77, 2012.
No citations: 21
[26] B. Makki and T. Eriksson, "Multiuser diversity in correlated Rayleigh-fading channels," *EURASIP Journal on Wireless Communications and Networking,* vol. 2012:38, 2012.
No citations: 2
[27] B. Makki and T. Eriksson, "On the Ergodic Achievable Rates of Spectrum Sharing Networks with Finite Backlogged Primary Users and an Interference Indicator Signal," *IEEE Transactions on Wireless Communications,* vol. 11, pp. 3079-3089, 2012.
No citations: 9
[28] J. Li, T. Eriksson, T. Svensson, and C. Botella, "Power Allocation for Two-Cell Two-User Joint Transmission," *IEEE Communications Letters,* vol. 16, pp. 1474-1477, 2012.
No citations: 5
[29] U. Gustavsson, T. Eriksson, H. M. Nemati, P. Saad, P. Singerl, and C. Fager, "An RF Carrier Bursting System using Partial Quantization Noise Cancellation," *IEEE Transactions on Circuits and Systems,* vol. 59, pp. 515-528, 2012.
No citations: 14

[30] H. Cao, H. M. Nemati, A. Tehrani Soltani, T. Eriksson, and C. Fager, "Digital Predistortion for High Efficiency Power Amplifier Architectures Using a Dual-input Modeling Approach," *IEEE Transactions on Microwave Theory and Techniques,* vol. 60, pp. 361-369, 2012.
No citations: 15
[31] S. Afsardoost, T. Eriksson, and C. Fager, "Digital Predistortion Using a Vector-Switched Model," *IEEE Transactions on Microwave Theory and Techniques,* vol. 60, pp. 1166 - 1174, 2012.
No citations: 19
[32] B. Makki and T. Eriksson, "On the Capacity of Rayleigh-Fading Correlated Spectrum Sharing Networks," *EURASIP Journal on Wireless Communications and Networking,* 2011.
No citations: 7
[33] B. Makki and T. Eriksson, "CSI feedback in correlated slow-fading channels," *IEEE Communications Letters,* 2011.
No citations: 5
[34] P. S. Kildal, A. Hussain, X. Chen, C. Orlenius, A. Skårbratt, J. Åsberg, T. Svensson, and T. Eriksson, "Threshold Receiver Model for Throughput of Wireless Devices with MIMO and Frequency Diversity Measured in Reverberation Chamber," *IEEE Antennas and Wireless Propagation Letters,* 2011.
No citations: 47
[35] S. Khademi, T. Svantesson, M. Viberg, and T. Eriksson, "Peak-to-Average-Power-Ratio (PAPR) Reduction in WiMAX and OFDM/A Systems," *EURASIP Journal on Advances in Signal Processing,* 2011.
No citations: 8
[36] S. Yousefi, J. Jaldén, and T. Eriksson, "Linear prediction of discrete-time 1/f processes," *IEEE Signal Processing Letters,* vol. 17, pp. 901-904, november 2010.
No citations: 5
[37] A. Soltani, H. Cao, S. Afsardoost, T. Eriksson, M. Isaksson, and C. Fager, "A Comparative Analysis of the Complexity/Accuracy Tradeoff in Power Amplifier Behavioral Models," *IEEE Transactions on Microwave Theory and Techniques,* vol. 58, pp. 1510-1520, June 2010.
No citations: 62
[38] D. Persson and T. Eriksson, "Power Series Quantization for Noisy Channels," *IEEE Transactions on Image Processing,* vol. 58, pp. 1405-1414, May 2010.
No citations: 3
[39] D. Persson and T. Eriksson, "On multiple description coding of sources with memory," *IEEE Transactions on Communications,* vol. 58, pp. 2242-2251, August 2010.
No citations: 4
[40] H. Nemati, H. Cao, B. Almgren, T. Eriksson, and C. Fager, "Design of Highly Efficient Load Modulation Transmitter for Wideband Cellular Applications," *IEEE Transactions on Microwave Theory and Techniques,* vol. 58, pp. 2820-2828, November 2010.
No citations: 21
[41] B. Makki and T. Eriksson, "On the Average Rate of Quasi-Static Fading Channels with ARQ and CSI Feedback," *IEEE Communications Letters,* vol. 14, pp. 806 - 808, September 2010.
No citations: 25
[42] B. Makki, L. Beygi, and T. Eriksson, "Channel Capacity Bounds in the Presence of Quantized Channel State Information," *EURASIP Journal on Wireless Communications and Networking,* vol. 2010, April 2010.

No citations: 8
[43] U. Gustavsson, T. Eriksson, and C. Fager, "Quantization Noise Minimization in SigmaDelta modulation based RF transmitter architectures," *IEEE Transactions on Circuits and Systems,* vol. 57, pp. 3082 - 3091, December 2010.
No citations: 9
[44] H. Cao, H. M. Nemati, A. Soltani, T. Eriksson, and C. Fager, "Linearization of Efficiency-Optimized Dynamic Load Modulation Transmitter Architectures," *IEEE Transactions on Microwave Theory and Techniques,* vol. 58, pp. 873-881, April 2010.
No citations: 38
[45] T. Svensson, T. Frank, T. Eriksson, M. Sternad, and A. Klein, "Block Interleaved Frequency Division Multiple Access for Power Efficiency, Robustness, Flexibility, and Scalability," *EURASIP Journal on Wireless Communications and Networking,* March 2009.
No citations: 14
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2 Peer-reviewed conference contributions

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[8] Juzi Zhao, Henk Wymeersch, and Erik Agrell, "Nonlinear impairment aware resource allocation in elastic optical networks," in *Proc. Optical Fiber Communication Conference (OFC),* Los Angeles, CA, Mar. 2015. *Number of citations: –.*

[9] Tobias A. Eriksson, Pontus Johannisson, Erik Agrell, Peter A. Andrekson, and Magnus Karlsson, "Experimental comparison of PS-QPSK and LDPC-coded PM-QPSK with equal spectral efficiency in WDM transmission," in *Proc. European Conference on Optical Communication (ECOC),* Cannes, France, Sept. 2014. *Number of citations: –.*

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[12] Christian Häger, Alexandre Graell i Amat, Fredrik Brännström, Alex Alvarado, and Erik 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.*

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3 Research review articles and invited presentations

[1] Henk Wymeersch *et al.*, invited paper (not yet submitted) at *Tyrrhenian International Workshop on Digital Communications*, Firenze, Italy, Sept. 2015. *Number of citations: –.*

[2] Alex Alvarado, Erik Agrell, *et al.*, "Coding and modulation for optical communication systems: Replacing the soft FEC limit paradigm," invited presentation (no paper) at *Canadian Workshop on Information Theory (CWIT)*, St. John's, Newfoundland and Labrador, Canada, July 2015. *Number of citations: –.*

[3] Ben Puttnam *et al.*, "Multi-core modulation formats for spatial superchannels," invited presentation (no paper) at *International Symposium on Ultrafast Photonic Technologies (ISUPT/EXAT)*, Kyoto, Japan, July 2015. *Number of citations: –.*

[4] Magnus Karlsson, Cristian B. Czegledi, and Erik Agrell, "Coherent transmission channels as 4d rotations," invited paper in *Proc. Signal Processing in Photonics Communications (SPPCom)*, Boston, MA, June–July 2015. *Number of citations: –.*

[5] Henk Wymeersch, Naga V. Irukulapati, Isaac Sackey, Pontus Johannisson, and Erik Agrell, "Backward Particle Message Passing," invited paper in *Proc. IEEE International*

Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Stockholm, Sweden, June–July 2015. *Number of citations: –.*

[6] Alexandre Graell i Amat, Christian Häger, Fredrik Brännström, and Erik Agrell, "Spatially-coupled codes for optical communications: State-of-the-art and open problems," invited paper in *Proc. OptoElectronics and Communication Conference (OECC),* Shanghai, China, June–July 2015. *Number of citations: –.*

[7] Erik Agrell, Alex Alvarado, and Frank R. Kschischang, "Implications of information theory in optical communications," invited paper in *Philosophical Transactions of the Royal Society A: Physical Sciences* and invited presentation at the *Royal Society Meeting,* London, U.K., May 2015. *Number of citations: –.*

[8] Erik Agrell and Giuseppe Durisi, "Information-theory-friendly models for fiber-optic channels: A primer," invited paper at *IEEE Information Theory Workshop,* Jerusalem, Israel, Apr.–May 2015. *Number of citations: –.*

[9] Henk Wymeersch, Naga V. Irukulapati, Domenico Marsella, Pontus Johannisson, Erik Agrell, and Marco Secondini, "On the use of factor graphs in optical communications," invited paper in *Proc. Optical Fiber Communication Conference (OFC),* Los Angeles, CA, Mar. 2015. *Number of citations: –.*

[10] Christian Häger, Alexandre Graell i Amat, Fredrik Brännström, Alex Alvarado, and Erik Agrell, "Terminated and tailbiting spatially coupled codes with optimized bit mappings for spectrally efficient fiber-optical systems," invited paper in *IEEE/OSA Journal of Lightwave Technology,* to appear, 2015. *Number of citations: –.*

[11] Erik Agrell, Alex Alvarado, Giuseppe Durisi, and Magnus Karlsson, "Capacity of a nonlinear optical channel with finite memory," invited paper in *IEEE/OSA Journal of Lightwave Technology,* vol. 32, no. 16, pp. 2862–2876, Aug. 2014. *Number of citations: 11.*

[12] Alex Alvarado, Leszek Szczecinski, and Erik Agrell, "On BICM receivers for TCM transmission," invited presentation (no paper) at *Swedish Communication Technologies Workshop (Swe-CTW),* Gothenburg, Sweden, Aug. 2013. *Number of citations: –.*

[13] Lotfollah Beygi, Erik Agrell, and Magnus Karlsson, "Adaptive coded modulation for nonlinear fiber-optical channels," invited presentation (no paper) at *Swedish Communication Technologies Workshop (Swe-CTW),* Gothenburg, Sweden, Aug. 2013. *Number of citations: –.*

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43. A. Papadogiannis, M. Färber, A. Saadani, D. Nisar, P. Weitkemper, Y. Sui, T. Svensson, D. Ktenas, Dimitri, N. Cassiau, T. M. de Moraes, “Advanced Relaying Concepts for Future Wireless Networks”, Future Network and Mobile Summit (FUNEMS 2012), Berlin, Germany, July 2012. Number of citations: **4**.
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47. M. R. Khanzadi, H. Mehrpouyan, E. Alpman, T. Svensson, D. Kuylenstierna, T. Eriksson, “On Models, Bounds, and Estimation Algorithms for Time-Varying Phase Noise”, 5th International Conference on Signal Processing and Communication Systems (ICSPCS2011), 2011. Number of citations: **12**.
48. R. Krishnan, H. Mehrpouyan, T. Eriksson, T. Svensson, “Optimal and Approximate Methods for Detection of Uncoded Data with Carrier Phase Noise”, IEEE Globecom, 2011. Number of citations: **5**.
49. J. Li, T. Svensson, C. Botella, T. Eriksson, X. Xu, X. Chen, “Joint Scheduling and Power Control in Coordinated Multi-Point Clusters”, 2011 IEEE 74th Vehicular Technology Conference: VTC2011-Fall 5-8 September 2011, San Francisco, United States. pp. 1-5. ISBN/ISSN: 978-1-4244-8328-0. Number of citations: **15**.
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51. Y. Sui, D. Aronsson, T. Svensson, “Evaluation of Link Adaptation Methods in Multi-User OFDM Systems with Imperfect Channel State Information”, Future Network & Mobile Summit, 2011. Number of citations: **1**.
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57. H. Mehrpouyan, S. D. Blostein, T. Svensson, "A New Distributive Approach for Achieving Timing Synchronization in Heterogenous Networks", ICC Workshop on Heterogeneous Networks, 2011. Number of citations: **0**.
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61. M. P. Wylie-Green, T. Svensson, E. Perrins, "Power and Spectrally Efficient Multiple Access Using CPM over SC-FDMA", Proc. IEEE Vehicular Technology Conference, VTC2010-Spring, 2010. Number of citations: **0**.
62. M. P. Wylie-Green, T. Svensson, "Throughput, Capacity, Handover and Latency Performance in a 3GPP LTE FDD Field Trial", GLOBECOM - IEEE Global Telecommunications Conference, Dec 6-10, 2010, Miami, USA, ISBN/ISSN: 978-142445638-3. Number of citations: **19**.
63. J. Karout, S. L. Muppirisetty, T. Svensson, "Performance Trade-off Investigation of B-IFDMA", IEEE Vehicular Technology Conference Fall, Sept. 2009, Anchorage, USA, pp. 368-372 . ISBN/ISSN: 978-1-4244-2514-3. Number of citations: **1**.
64. H. Zhang, J. Li, X. Xu, T. vensson, C. Botella, S. Lee, "Channel allocation based on Kalman filter prediction for downlink OFDMA systems", IEEE Vehicular Technology Conference Fall, Sept. 2009, Anchorage, USA. , ISBN/ISSN: 978-1-4244-2515-0. Number of citations: **5**.
65. D. Aronsson, T. Svensson, M. Sternad, "Performance Evaluation of Memory-less and Kalman-based Channel Estimation for OFDMA", Proceedings IEEE Vehicular Technology Conference Spring, April 2009, Barcelona, Spain. Number of citations: **5**.
66. M. Boldi, T. Svensson, et al. "Coordinated MultiPoint Systems for IMT-Advanced in the Framework of Winner+ Project", ICT Mobile Summit 2009, Santander, Spain, June 2009. Number of citations: **2**.
67. C. Botella, F. Domene, G. Pinero, T. Svensson, "A low-complexity joint power control and beamforming algorithm for the downlink of multi-user W-CDMA coordinated systems", Proc. IEEE International Workshop on Signal Processing Advances for Wireless Communications (SPAWC09), 2009. Number of citations: **2**.
68. * T. Svensson, A. Svensson, "Design and Performance of Constrained Envelope Continuous Phase Modulation", (Invited paper). Proceedings IEEE 4th International Waveform Diversity and Design Conference, Feb 2009, Orlando, Florida. Number of citations: **1**.
69. M. P. Wylie-Green, E. Perrins, T. Svensson, "Design and Performance of a Multiple Access CPM-SC-FDMA Transmission Scheme", Proceedings IEEE 4th International Waveform Diversity and Design Conference, Feb 2009, Orlando, Florida. Number of citations: **4**.
70. M. Sternad, T. Svensson, M. Döttling, "Resource Allocation and Control Signaling in the WINNER flexible MAC Concept", Proceedings IEEE Vehicular Technology Conference Fall, Calgary, Canada, Sep 2008. Number of citations: **11**.

71. C. Wijting, K. Doppler, K. Kalliojärvi, N. Johansson, J. Nyström, M. Olsson, A. Osseiran, M. Döttling, J. Luo, T. Svensson, M. Sternad, G. Auer, T. Lestable, S. Pfletschinger, "WINNER II System Concept: Advanced Radio Technologies for Future Wireless Systems", ICT Mobile Summit 2008, Stockholm, Sweden, June 2008. Number of citations: **14**.
72. S. Plass, T. Svensson, A. Dammann, "Block-equidistant resource mapping in OFDM, MC-CDMA and SS-MC-MA", 12th International OFDM Workshop, Hamburg, Germany, August 2007. Number of citations: **3**.
73. T. Svensson, T. Frank, D. Falconer, M. Sternad, E. Costa, A. Klein, "BIFDMA - A Power Efficient Multiple Access Scheme for Non-frequency-adaptive Transmission", IST Mobile Summit 2007, Budapest, July 2007. Number of citations: **46**.

EU Project deliverables

METIS projects deliverables (https://www.metis2020.com/documents/deliverables/):

1. F. Schaich, ..., T. Svensson, et al. EU FP7 INFSO-ICT-317669 METIS, D2.3 "Components of a new air interface - building blocks and performance", April 2014.
2. R. Fantini, ..., T. Svensson, et al. EU FP7 INFSO-ICT-317669 METIS, D3.2 "First performance results for multi-node/multi-antenna transmission technologies", April 2014.
3. E. Pollakis, ..., T. Svensson, et al. EU FP7 INFSO-ICT-317669 METIS, D4.2 "Final report on trade-off investigations", Sep 2014
4. P. Weitkemper, ..., T. Svensson, et al. EU FP7 INFSO-ICT-317669 METIS, D2.2 "Novel radio link concepts and state of the art analysis", Oct 2013.
5. N. Brahmi, V. Venkatasubramanian, ..., T. Svensson, et al. EU FP7 INFSO-ICT-317669 METIS, D4.1 "Summary on preliminary trade-off investigations and first set of potential network-level solutions", Sep 2013.
6. E. Lähetkangas, H. Lin, ..., T. Svensson, et al. EU FP7 INFSO-ICT-317669 METIS, D2.1 "Requirement analysis and design approaches for 5G air interface", Aug 2013.
7. E. de Carvalho, P. Popovski, H. Thomsen (AAU)..., T. Svensson, et al. EU FP7 INFSO-ICT-317669 METIS, D3.1 "Positioning of multi-node/multi-antenna technologies", July 2013.
8. M. Fallgren, B. Timus, ..., T. Svensson, et al. EU FP7 INFSO-ICT-317669 METIS, D1.1 "Future radio access scenarios, requirements and KPIs", April 2013.

ARTIST4G projects deliverables (https://ict-artist4g.eu/):

9. D. Gesbert, T. Svensson, et al. EU FP7 INFSO-ICT-247223 ARTIST4G, D1.4 "Interference Avoidance Techniques and System Design", July 2012.
10. C. Pietsch, S. Brueck, …, T. Svensson, et al. EU FP7 INFSO-ICT-247223 ARTIST4G, D3.5 "Performance evaluation of Advanced relay concept", July 2012.
11. M. Grieger, J. Koppenborg, ..., T. Svensson, et al. EU FP7 INFSO-ICT-247223 ARTIST4G, D6.3 "Laboratory and field trial results connected to the second set of innovations", July 2012.
12. Aronsson, Daniel; Bonneville, Hervé; Fan, Bin; Färber, Michael; Góra, Jacek; Khanfouci, Mourad; Liebl, Guenther; Martins de Moraes, Thiago; Nicolov, Alexandre; Redana, Simone; Saadani, Ahmed; Seidel, Eiko; Sternad, Mikael; Svensson, Tommy; Vihriälä, Jaakko: EU FP7 INFSO-ICT-247223 ARTIST4G, D3.4 Relay configurations, 2011.
13. Bonneville, Hervé; Brueck, Stefan; Färber, Michael; Gesbert, David; Góra, Jacek; Gresset, Nicolas; Hatefi, Atoosa; Khanfouci, Mourad; Kténas, Dimitri; Liebl, Guenther; Martins de Moraes, Thiago; Nahas, Michel; Pietsch, Christian; Plainchault, Mélanie; Redana, Simone; Saadani, Ahmed; Seidel, Eiko; Svensson, Tommy; Taoka, Hidekazu; Valentin, Stefan; Weitkemper, Petra; Yilmaz, Erhan: EU FP7 INFSO-ICT-247223 ARTIST4G, D3.2 Advanced Relay Technical Proposals, 2011.
37. Botella, Carmen; Brunel, Loïc; Ciochina, Cristina; Cottatellucci, Laura; D'Amico, Valeria; Kerret, Paul de; Gesbert, David; Giese, Jochen; Gresset, Nicolas; Guillet, Julien; Halbauer, Hardy; Jiang, Xiaoran; Khanfir, Hajer; Lakshmana, Tilak Rajesh; Melis, Bruno; Sabella, Dario; Saur, Stephan; Svensson, Tommy; Tortelier, Patrick; Zirwas, Wolfgang: EU FP7 INFSO-ICT-247223 ARTIST4G, D1.3 Innovative scheduling and cross-layer design techniques for interference avoidance, 2011.

38. Koppenborg, Johannes; Hoek, Cornelis; Grieger, Michael; Diehm, Fabian; Dutoit, Denis; Kténas, Dimitri; Chrabieh, Rabih; Sezginer, Serdar; Sternad, Mikael; Svensson, Tommy; Zirwas, Wolfgang: EU FP7 INFSO-ICT-247223 ARTIST4G, D6.1 First feedback on implementation aspects connected to the selected innovations, 2011.
39. D'Amico, Valeria; Gresset, Nicolas; Botella, Carmen; Cottatellucci, Laura; Doll, Mark; Fritzsche, Richard; Gesbert, David; Giese, Jochen; Halbauer, Hardy; Hardouin, Eric; Khanfir, Hajer; Pablo, Maria Luz; Saur, Stephan; Svensson, Tommy; Zirwas, Wolfgang: EU FP7 INFSO-ICT-247223 ARTIST4G, D1.1 Definitions and architecture requirements for supporting interference avoidance techniques, 2010.
40. D'Amico, Valeria; Halbauer, Hardy; Aronsson, Daniel; Botella, Carmen; Brueck, Stefan; Ciochina, Cristina; Eriksson, Thomas; Fritzsche, Richard; Gesbert, David; Giese, Jochen; Gresset, Nicolas; Lakshmana, Tilak Rajesh; Makki, Behrooz; Melis, Bruno; Abildgaard Olesen, Rikke; Pablo, Maria Luz; Phan Huy, Dinh Thuy; Saur, Stephan; Sternad, Mikael; Svensson, Tommy; Zakhour, Randa; Zirwas, Wolfgang: EU FP7 INFSO-ICT-247223 ARTIST4G, D1.2 Innovative advanced signal processing algorithms for interference avoidance., 2010.
41. Gora, Jacek; Gouraud, Alexandre; Marsch, Patrick; Gresset, Nicolas; Karray, Mohamed; Irmer, Ralf; Lu, Amy; D'Amico, Valeria; Halbauer, Hardy; Saur, Stephan; Thielecke, Gunther; Koppenborg, Johannes; Giese, Jochen; Schoeneich, Hendrik; Weitkemper, Petra; Redana, Simone; Svensson, Tommy: EU FP7 INFSO-ICT-247223 ARTIST4G, D5.1 Scenarios, Key Performance Indicators and Evaluation Methodology for Advanced Cellular Systems, 2010.
42. Khanfouci, Mourad; Redana, Simone; Bonneville, Hervé; Braun, Volker; Brück, Stefan; Cesar, Bozo; Fantini, Roberto; Färber, Michael; Gora, Jacek; He, Xiaoben; Kténas, Dimitri; Liebl, Guenther; de Moraes, Thiago Martins; Saadani, Ahmed; Seidel, Eiko; Svensson, Tommy; Pietsch, Christian; Weitkemper, Petra; Zirwas, Wolfgang: EU FP7 INFSO-ICT-247223 ARTIST4G, D3.1 Definitions and Architecture requirements for supporting Advanced Relay concepts, 2010.

WINNER projects deliverables (http://projects.celtic-initiative.org/winner+/):
43. Osseiran, Afif; Auer, Gunther; Mehdi, Bennis; Boldi, Mauro; Gouraud, Alexandre; Jungnickel, Volker; Mayrargue, Sylvie; Mihovska, Albena; Monserrat, Jose; Sroka, Pawel; Svensson, Tommy; Tölli, Antti; Vihriälä, Jaakko; Thiele, Lars; Zinovieff, Eric: CELTIC CP5-026 WINNER+, D2.2 Enabling Techniques for LTE-A and beyond, 2010.
44. Svensson, Tommy; Zinovieff, Eric; Auer, Gunther; Bennis, Mehdi; Boldi, Mauro; Botella, Carmen; Brunel, Loic; Calvanese, Emilio; D'Amico, Valeria; Duchesne, Amelie; Greco, Paulo; Jungnickel, Volker; Komulainen, Petri; Ktenas, Dimitri; Liu, Yang; Mayrargue, Sylvie; Melis, Bruno; Mihovska, Albena; Monserrat, Jose; Olsson, Magnus; Osseiran, Afif; Pennanen, Harri; Rasmussen, Lars; Roemer, Florian; Rost, Peter; Savin, Valentin; Schoenen, Rainer; Sezginer, Serdar; Sroka, Pawel; Thiele, Lars; Tölli, Antti; Vihriälä, Jaakko; Vivier, Guillaume; Wesolowski, Krzysztof; Xiao, Ming: CELTIC CP5-026 WINNER+, D1.9 Final Innovation Report, 2010.
45. Auer, Gunther; Cabrejas, Jorge; Calvanese, Emilio; Clessienne, Thierry; Greco, Paulo; Wylie-Green, Marilynn P.; Ktenas, Dimitri; Martín-Sacristán, David; Mihovska, Albena; Monserrat, Jose; Otyakmaz, Arif; Rossi, Roberto; Saul, Andreas; Sroka, Pawel; Svensson, Tommy: CELTIC CP5-026 WINNER+, D1.5 Intermediate Report on System Aspect of Advanced RRM, 2009.
46. Boldi, Mauro; Botella, Carmen; Boccardi, Federico; D'Amico, Valeria; Hardouin, Eric; Olsson, Magnus; Pennanen, Harri; Rost, Peter; Savin, Valentin; Svensson, Tommy; Tölli, Antti: CELTIC CP5-026 WINNER+, D1.8 Intermediate Report on CoMP (Coordinated Multi-Point) and Relaying in the Framework of CoMP, 2009.
47. Osseiran, Afif; Gouraud, Alexandre; Svensson, Tommy; Boldi, Mauro; D'Amico, Valeria; Hardouin, Eric; Monserrat, Jose; Otyakmaz, Arif; Saul, Andreas; Tölli, Antti; Vihriälä, Jaakko; Bennis, Mehdi; Mihovska, Albena: CELTIC CP5-026 WINNER+, D2.1 Preliminary WINNER+ System Concept, 2009.
48. Bengtsson, Mats; Shankar, Bhavani; Björnson, Emil; Boccardi, Federico; Boldi, Mauro; D'Amico, Valeria; Fehske, Albrecht; Fuchs, Martin; Hardouin, Eric; Komulainen, Petri; Melis, Bruno; Olsson, Magnus; Papadogiannis, Agisilaos; Pennanen, Harri; Rost, Peter; Saadani, Ahmed; Schellmann,

Malte; Svensson, Tommy; Thiele, Lars; Tölli, Antti; Wild, Thorsten: CELTIC CP5-026 WINNER+, D1.4 Initial Report on Advanced Multiple Antenna Systems, Dec 2008.
49. Aronsson, Daniel; Auer, Gunther; Svensson, Tommy; et., al: EU FP6 IST-4-027756 WINNER II, D2.3.3 Link level procedures for the WINNER System, Nov 2007.
50. Auer, Gunther; Döttling, Martin; Svensson, Tommy; et., al: EU FP6 IST-4-027756 WINNER II, D6.13.14 WINNER II System Concept Description, Dec 2007.
51. Irmer, Ralf; Döttling, Martin; Svensson, Tommy; et., al: EU FP6 IST-4-027756 WINNER II, D6.13.10 Final CG wide area description for integration into overall System Concept and assessment of key technologies, Nov 2007.
52. Lestable, Thierry; Ma, Yi; Svensson, Tommy; et., al: EU FP6 IST-4-027756 WINNER II, D2.2.3 Modulation and Coding schemes for the WINNER II System, Nov 2007.
53. Rouquette-Lveil, Stephanie; Auer, Gunther; Svensson, Tommy; et., al: EU FP6 IST-4-027756 WINNER II, D6.13.12 Final CG local area description for integration into overall System Concept and assessment of key technologies, Oct 2007.

3. Monographs

1. * T. Svensson, ”Spectrally Efficient Continuous Phase Modulation”, Gothenburg, Chalmers University of Technology. Ph.D. thesis, Technical report 435, Dec. 2002. Number of citations: **5.**
2. T. Svensson, “On Spectrally Efficient Continuous Phase Modulation”, Gothenburg, Chalmers University of Technology, Licentiate thesis, Technical report 363L, Nov. 2000. Number of citations: **7.**

4. Research review articles

None.

5. Books and book chapters

1. Book chapter in: A. Osseiran, W. Mohr, J. Monserrat, …, T. Svensson, et, al., “Mobile and wireless communications for IMT-A and beyond”, ISBN/ISSN: 978-1-1199-9321-6, 2011. Number of citations: **33**.
2. Book chapter in: W. Mohr, M. Döttling, A. Osseiran, …, T. Svensson, et, al., “Radio Technologies and Concepts for IMT-Advanced”. Wiley Nov. 2009. ISBN/ISSN: 978-0-470-74763-6. Number of citations: **4**.

6. Patents

No patent granted, but one submitted. IPR rights are sold to Ericsson AB, Dec 2014.

7. Open access computer programs or databases you have developed

None.

8. Popular-scientific articles/presentations

1. Numerous invited talks at Ericsson AB in Sweden/ Italy/ China, 2005-present
2. Numerous technical presentations within EU projects (WINNER, ARTIST4G, METIS), 2004-present
3. Invited speaker with three talks related to Heterogeneous networks, Moving networks, and Radio link enablers at METIS 5G Global Summit, Berlin, Oct 2014.
4. Invited speaker “Challenges and research towards 5G” at EURECOM, Sep 2013, and University of Oulu, Dec 2013.
5. Invited guest lecturer in Communication Engineering Master Program course SSY145 “Wireless Networks” on Future wireless systems technologies, Department of Signals and Systems, Chalmers University of Technology, Sweden, 2009-2014.
6. Invited speaker at Huawei 5G@Europe, Munich, Feb 2014.
7. Invited speaker at Huawei Research Shanghai R&D center, April 2013.
8. Invited speaker at Orange Labs, Oct 2012.

9. Tutorial on “Coordinated Multi-Point in Cellular Networks” at ICC’2013, June 2013, Hungary, SweCTW’2013, Aug 2013, Sweden, ISWCS’2013, Aug 2013, Germany.
10. Invited speaker at Chongqing University of Posts and Telecommunications, 2012.
11. Invited speaker at Beijing University of Posts and Telecommunications, 2010.
12. Invited speaker at Ericsson AB Göteborg, Ericsson AB Mölndal, Ericsson AB Milano, Ericsson Research Stockholm, Ericsson Research Beijing at several occasions during 2005-2013.
13. Invited speaker with title ”Visions and technologies for IMT Advanced and Beyond” at the CHASE workshop Oct 22-23, 2008.
14. Invited speaker with titles ”Technologies and impacts on spectrum management” and ”Visions of IMT Advanced and Beyond” at the Future Spectrum Management workshops at Chalmers with the National Telecommunications Commission, Thailand during Jan 31-Feb 1 and April 15-16, respectively, 2008.
15. Invited speaker at the European Commission FP7 Consultation Meeting: Future Mobile and Wireless Radio Systems, Feb 6, 2008, with the aim to influence coming FP7 call profiles.
16. Haardt, Martin; Stuckmann, Peter; Zimmermann, Rainer; Svensson, Tommy; et., al: Report on the FP7 Consultation Meeting, Future Mobile and Wireless Radio Systems: Challenges in European Research., Feb 2008. ftp://ftp.cordis.europa.eu/pub/fp7/ict/docs/future-networks/20080206-future-mobile-and-wireless-radio-systems-report en.pdf
17. Invited speaker at the Wireless World Initiative (WWI) Innovation Day, Brussels, Nov 2007, describing our main innovations within the WINNER II system concept.
18. Guest lecturer on future wireless networks in the course ITS031, Computers, Communication, and Social Networks, 2006, within the undergraduate school at Chalmers Technology Management and Economics.

Pedagogical science publication:

1. Svensson, Tommy: Retrospective Analysis of ESS166 Kommunikationssystem E3. Pedagogical Papers Series, vol.3, Winter 2009,

Articles in IEEE Communications Magazine describing the Swedish IEEE VT/COM Section activities:

1. Hernandez, Juan; Nilsson, Jan; Svensson, Tommy; Timus, Bogdan; Wilhelmsson, Leif R., ”Age vs. Time Speed at Sweden ComSoc”, IEEE Communications Magazine, March 2009.
2. Hernandez, Juan; Nilsson, Jan; Svensson, Tommy; Timus, Bogdan; Wilhelmsson, Leif R., ”A White Green Scenario for Communications”, IEEE Communications Magazine, June 2008.

List of publications (2008-2015) – Christian Fager

- Citation merits: Google Scholar, 2015-03-28
- Complete list of publications: http://scholar.google.se/citations?user=57OMjKQAAAAJ.
- Citations given: total / without self-citations

Five most cited publications (all years)

[X1] S. E. Gunnarsson, C. Kärnfelt, H. Zirath, R. Kozhuharov, D. Kuylenstierna, A. Alping, and **C. Fager**, "Highly integrated 60 GHz transmitter and receiver MMICs in a GaAs pHEMT technology," *IEEE Journal of Solid-State Circuits*, vol. 40, pp. 2174-86, 2005.

Number of citations: 120/106

[X2] **C. Fager**, J. C. Pedro, N. B. Carvalho, and H. Zirath, "Prediction of IMD in LDMOS transistor amplifiers using a new large-signal model," *IEEE Transactions on Microwave Theory and Techniques*, vol. 50, pp. 2834-42, 2002.

Number of citations: 107/102

[X4] **C. Fager**, J. C. Pedro, N. B. Carvalho, H. Zirath, F. Fortes, and M. J. Rosário, "A comprehensive analysis of IMD behavior in RF CMOS power amplifiers," *IEEE Journal of Solid-State Circuits*, vol. 39, pp. 24-34, 2004.

Number of citations: 89/89

[X3]* H. M. Nemati, **C. Fager**, U. Gustavsson, R. Jos, and H. Zirath, "Design of Varactor-Based Tunable Matching Networks for Dynamic Load Modulation of High Power Amplifiers," *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, pp. 1110 - 1118, 2009.

Number of citations: 86/70

[X5] S. E. Gunnarsson, C. Karnfelt, H. Zirath, R. Kozhuharov, D. Kuylenstierna, **C. Fager**, M. Ferndahl, B. Hansson, A. Alping, and P. Hallbjorner, "60 GHz Single-Chip Front-End MMICs and Systems for Multi-Gb/s Wireless Communication," *IEEE Journal of Solid-State Circuits*, vol. 42, pp. 1143-1157, 2007.

Number of citations: 80/74

1. Peer-reviewed journal publications

[J1] S. Gustafsson, M. Thorsell, J. Stenarson, and **C. Fager**, "An oscilloscope correction method for vector-corrected RF measurements," to appear in *IEEE Trans. Instrumentation and Measurements*, 2015.
Number of citations: 0/0

[J2] A. Prasad, **C. Fager**, M. Thorsell, C. M. Andersson, and K. Yhland, "Symmetrical Large-Signal Modeling of Microwave Switch FETs," *IEEE Trans. Microwave Theory Tech.*, vol. 62, pp. 1590 – 1598, 2014.
Number of citations: 1/0

[J3] D. Gustafsson, J. Chani Cahuana, D. Kuylenstierna, I. Angelov, and **C. Fager**, "A GaN MMIC modified Doherty PA with large bandwidth and reconfigurable efficiency," *IEEE Trans. Microwave Theory Tech.*, vol. 62, pp. 3006-3016, 2014.
Number of citations: 0/0

[J4] L. Piazzon, P. Saad, P. Colantonio, F. Giannini, K. Andersson, and **C. Fager**, "Design method for quasi-optimal multiband branch-line couplers," *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 24, pp. 117-129, 2014.
Number of citations: 0/0

[J5] C. M. Andersson, D. Gustafsson, J. Chani Cahuana, R. Hellberg, and **C. Fager**, "A 1-3 GHz Digitally Controlled Dual-RF Input Power Amplifier Design Based on a Doherty-Outphasing Continuum Analysis," *IEEE Trans. Microwave Theory Tech.*, vol. 61, pp. 3743-3752, 2013.
Number of citations: 7/6

[J6] P. Saad, M. Thorsell, K. Andersson, and **C. Fager**, "Investigation of Push-Pull Microwave Power Amplifiers Using an Advanced Measurement Setup," *IEEE Microwave and Wireless Components Letters*, vol. 23, pp. 220-222, 2013.
Number of citations: 2/1

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Number of citations: 19/6

[J13] L. Piazzon, P. Saad, P. Colantonio, F. Giannini, K. Andersson, and **C. Fager**, "Branch-Line Coupler Design Operating in Four Arbitrary Frequencies," *IEEE Microwave and Wireless Components Letters*, vol. 22, pp. 67-69, 2012.
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Number of citations: 17/13

2. Peer-reviewed conference publications

[C1] M. Pampin-Gonzalez, M. Özen, C. Sanchez-Perez, J. Chani Cahuana, and **C. Fager**, "Outphasing Combiner Synthesis from Transistor Load Pull Data," *accepted for presentation at IEEE International Microwave Symposium (IMS)* 2015
Number of citations: -/-

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Number of citations: 0/0

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Number of citations: 7/6

[C25] P. Saad, P. Colantonio, J. Moon, L. Piazzon, K. Andersson, B. Kim, and **C. Fager**, "Concurrent Dual-Band GaN-HEMT Power Amplifier at 1.8 GHz and 2.4 GHz," *Proc IEEE Wireless and Microwave Technology Conference (WAMICON)*, April 2012.
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Number of citations: 1/1

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[C45] A. Soltani Tehrani, H. Cao, T. Eriksson, and **C. Fager**, "Orthonormal Basis Power Amplifier Model Reduction," *Proc. 2008 International Workshop on Integrated Nonlinear Microwave and Millimeter-Wave Circuits*, Malaga, Spain, 2008.
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[C47] P. Landin, **C. Fager**, M. Isaksson, and K. Andersson, "Power Amplifier Behavioral Modeling Performance Comparison of the LSNA and the modulation-domain system," *Proc. 72nd ARFTG Microwave Measurement Conference*, Portland, USA., 2008.
Number of citations: 4/3

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Number of citations: 4/4

[C49] M. Abbasi, S. E. Gunnarsson, R. Kozhuharov, C. Kärnfelt, **C. Fager**, D. Kuylenstierna, C. Stoij, and H. Zirath, "Integrated 60 GHz Circuits and Systems for High-Speed Communications," *Proc. European Microwave Integrated Circuit Conference* (EuMIC), Amsterdam, The Netherlands, pp. 9-12, 2008.
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Number of citations: 20/12

3. Monographs

4. Books and book chapters

5. Books and book chapters

[B1] M. Rudolph, **C. Fager**, and D. Root: *Nonlinear Transistor Model Parameter Extraction Techniques*," Cambridge: Cambridge University Press, 2011.
Number of citations: 21/18

[B2] **C. Fager**, K. Andersson, and M. Ferndahl, "Uncertainties in small-signal equivalent circuit modeling," in *Nonlinear Transistor Model Parameter Extraction Techniques*, (M. Rudolph, **C. Fager**, and D. Root, Eds). Cambridge: Cambridge University Press, 2011, pp. 86-120.
Number of citations: 0/0

[B3] **C. Fager**, "Understanding and prediction of IMD behaviour in power amplifiers," in Characterization and Modelling Approaches for Advanced Linearisation Techniques, *J. A. Garcia and J. M. Z. Sainz de la Maza, Eds. Kerala, India: Research Signpost*, 2005.
Number of citations: 0/0

6. Patents

[P1] M. Özen and **C. Fager**, "Amplifier Apparatus and Method," PCT/EP2013/071631, Patent Pending.

[P2] D. Gustafsson and **C. Fager**, "Wideband and Reconfigurable Doherty Based Amplifier," WO Patent 2,012,149,976; 2012.

[P3] D. Weinholt, **C. Fager**, G. Skatt, and K. Jarl, "Apparatus in a microwave system," WO Patent 2,002,080,393, 2002

7. Open Access Software (publicly available)

[S1] "muwave Matlab toolbox," https://github.com/extrakteon/muwave, 2009–.

8. Popular science presentation

[PS1] **C. Fager**, "Energieffektiva Radiosändare för Framtidens Kommunikationssystem," ELEKTRONIK2011, Göteborg, 2011.

CV

Name: Thomas Eriksson	**Doctorial degree:** 1996-11-06
Birthdate: 19640407	**Academic title:** Professor
Gender: Male	**Employer:** No current employer

Research education

Dissertation title (swe)
Vector quantization in speech coding

Dissertation title (en)
Vector quantization in speech coding

Organisation	Unit	Supervisor
Chalmers tekniska högskola, Sweden Sweden - Higher education Institutes	Inst för Signaler och system	Per Hedelin

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
20204. Telekommunikation		1996-11-06

CV

Name: Tommy Svensson	**Doctorial degree:** 2003-03-25
Birthdate: 19700120	**Academic title:** Docent
Gender: Male	**Employer:** Chalmers tekniska högskola

Research education

Dissertation title (swe)

Spektral-effektiv kontinuerlig fasmodulation

Dissertation title (en)

Spectrally Efficient Continuous Phase Modulation

Organisation	Unit	Supervisor
Chalmers tekniska högskola, Sweden Sweden - Higher education Institutes	3204 - Kommunikationssystem	Arne Svensson

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
20203. Kommunikationssystem	91-7291-244-8	2003-03-25

CV

Name: Erik Agrell	**Doctorial degree:** 1997-04-14
Birthdate: 19651122	**Academic title:** Professor
Gender: Male	**Employer:** No current employer

Research education

Dissertation title (swe)
Voronoi-Based Coding

Dissertation title (en)
Voronoi-Based Coding

Organisation	Unit	Supervisor
Chalmers tekniska högskola, Sweden Sweden - Higher education Institutes	Inst för informationsteori	Per Hedelin

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
20204. Telekommunikation	91-7197-464-4	1997-04-14

CV

Name: Christian Fager	**Doctorial degree:** 2003-06-13
Birthdate: 19741130	**Academic title:** Docent
Gender: Male	**Employer:** Chalmers tekniska högskola

Research education

Dissertation title (swe)

Dissertation title (en)

Microwave FET Modeling and Applications

Organisation	Unit	Supervisor
Chalmers tekniska högskola, Sweden Sweden - Higher education Institutes	59100 - Mikrovågselektronik	Herbert Zirath

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
20204. Telekommunikation	91-7291-286-3	2003-06-13

Publications

Name: Thomas Eriksson	**Doctorial degree:** 1996-11-06
Birthdate: 19640407	**Academic title:** Professor
Gender: Male	**Employer:** No current employer

Eriksson, Thomas has not added any publications to the application.

Publications

Name: Tommy Svensson	**Doctorial degree:** 2003-03-25
Birthdate: 19700120	**Academic title:** Docent
Gender: Male	**Employer:** Chalmers tekniska högskola

Svensson, Tommy has not added any publications to the application.

Publications

Name: Erik Agrell	**Doctorial degree:** 1997-04-14
Birthdate: 19651122	**Academic title:** Professor
Gender: Male	**Employer:** No current employer

Agrell, Erik has not added any publications to the application.

Publications

Name: Christian Fager	**Doctorial degree:** 2003-06-13
Birthdate: 19741130	**Academic title:** Docent
Gender: Male	**Employer:** Chalmers tekniska högskola

Fager, Christian 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.