Application

2015-03-31

2015-05096	Rusek, Fredrik	NT-14

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Information about application

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

Type of grant: Projektbidrag

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Subject area:

Project title (english): Research of location aware 5G communications: Cluster Data Bases, Machine Learning Algorithms, Physical Layer Security, and Transmission Techniques

Project start: 2016-01-01

Project end: 2019-12-31

Review panel applied for: NT-14, NT-2, NT-1

Classification code: 20203. Kommunikationssystem, 20204. Telekommunikation, 20299. Annan elektroteknik och elektronik

Keywords: Massive MIMO, Radio propagation, Machine learning, databases, positioning and localization

Funds applied for

Year:	2016	2017	2018	2019
Amount:	907,086	856,770	876,940	897,600

Descriptive data

Project info

Project title (Swedish)*

Utforskning av positionsbaserad 5G kommunikation: Klusterdatabaser, maskinlärning, fysisk lagersäkerhet samt transmissionstekniker

Project title (English)*

Research of location aware 5G communications: Cluster Data Bases, Machine Learning Algorithms, Physical Layer Security, and Transmission Techniques

Abstract (English)*

In this project we consider massive MIMO systems where user terminals can be perfectly located in physical space. Then we aim at the construction of a database that tabulates the channel propagation characteristics for each point in space; in particular, we are interested in the visible clusters between each point and the base station. In order to build and maintain such a database advanced machine learning algorithms are needed.

With the database at hand, a number of interesting and appealing applications can be facilitated. For example, physical layer security can be made much more promising for massive MIMO, and the standard TDD assumption of massive MIMO can be easily abandoned. Furthermore, the overhead due to training and the problem of pilot contamination are almost entirely eliminated.

The main research questions lie in the nature of the propagation environment itself: Is the propagation environment of such a nature that a machine can be built that learns it over time? And if yes, to what extent can we "tabulate" the entire geometry around the base station? How rapid must we sound the environment in order to maintain the database, what sort of machine learning algorithms should be used? etc

In order to answer these questions, measurement campaings with Lund University's 100 antenna port testbed will be carried out. Different from earlier campaigns, the intented campaign will take place during the course of several days.

These are entirely new research questions that span across several fields, ranging from classical communication theory, signal processing, radio propagation, security, machine learning, databases, and big data.

Popular scientific description (Swedish)*

Detta projekt undersöker till vilken grad en basstation kan lära sig hela sitt närområde. Tack vara framsteg i positionering kan vi idag antaga att en basstation kan få tillförlitliga estimat av användares positioner. En databas kan då byggas upp som tabulerar kommunikationskanalen från basstationen till alla punkter i närområdet.

En sådan databas öppnar upp en helt ny värld av möjligheter för en basstation, men många hinder återstår att lösas innan en sådan databas kan bli verklighet. Detta projekt syftar till att lösa dessa återstående problem.

Project period

Number of project years*

4

Calculated project time*

2016-01-01 - 2019-12-31

Classifications

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

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

SCB-codes*	2. Teknik > 202. Elektroteknik och elektronik > 20203. Kommunikationssystem 2. Teknik > 202. Elektroteknik och elektronik > 20204. Telekommunikation 2. Teknik > 202. Elektroteknik och elektronik > 20299. Annan elektroteknik och elektronik

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

Keyword 1*

Massive MIMO

Keyword 2*

Radio propagation

Keyword 3*

Machine learning

Keyword 4

databases

Keyword 5

positioning and localization

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*

Inte relevant för detta projekt

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

Research of location aware 5G communications: Cluster Data Bases, Machine Learning Algorithms, Physical Layer Security, and Transmission Techniques.

FREDRIK RUSEK

March 30, 2015

1 Purpose and Aims

In a nutshell, this project aims at integrating the following well established technologies together:

- Massive MIMO (MaMIMO). This is a technique that equips base stations with several hundreds - or even thousands - antennas. By doing so, performance is dramatically improved.
- Physical Layer Security (PLS). Although discovered in the 70s, PLS has only recently gained momentum. By exploiting characteristics of the propagation channel, PLS is enabling secure communication without any formal cryptographic system. Hence, system design is much simpler with PLS as there is no key distribution.
- Coordinated Multipoint (COMP). In a COMP system base stations (BS) are connected via a backhaul network; this allows for reduced interference at user terminals.
- Terminal Localization. Due to recent advances on localiztion techniques, and to the global positioning system (GPS), accurate and relible estimates of the physical positions of user terminals can be foreseen in the near future; arguably already today.
- Radio Channel Propagation Theory. The amount of research devoted to radio propagation aspects of wireless channels is large, and today wireless channels are well understood.
- Machine Learning Algorithms. In complex systems optimal algorithms, no matter their purposes, are seldomly available. Therefore, machine learning algorithms that produce - in a fairly ad-hoc but still controlled fashion - outputs based on past observations are popular. These algorithms are today well researched and understood.
- Beamforming. Beamforming has been studied since the early days of multiple antenna (MIMO) systems and deals with spatial separation of multiple users.

Except for PLS these technologies constitute the basis for the upcoming 5G communication system. Of course, 5G will also contain a few other techniques, such as mmWave, densification, possibly improved modulation types etc.

Simply put, the purpose of this project is to research ways to combine the aforementioned techniques in a way so that they maximally benefit from each other. For example, to what extent can a MaMIMO system benefit from accurate physical localization of the terminals? - and more fundamentally, *how* should the two fields be linked? The focal point in this project to link the fields will be the research of an entirely new theme termed the *cluster data base*. The aim of the project is to develop an entirely new network structure for 5G systems (and beyond). If successful, the envisioned system will

- Use very low training data, thereby reducing the loss of spectral efficiency due to training.
- Abandon formal cryptographic systems and rely on PLS.
- The pilot contamination problem, which is a severe problem in MaMIMO systems, is alleviated.
- Implement MaMIMO in non-time-division-duplex (TDD) modes.
- Allow considerably simpler processing at base stations.

It may come across as if the project is purely industrial but this is definitely not the case as there are many fundamental questions that must be addressed; these will be discussed in forthcoming sections.

2 Survey of the Field

The system to be researched in the project is new and the applicant is not aware of any earlier attempts to synthesize a similar system. Therefore, we shall briefly survey a few of the individual fields to be integrated, before giving a detailed description of the envisioned system and the challenges that must be researched before it can become a reality.

2.1 Massive MIMO

This is a fairly recent technology [1] but has received huge attention and can today be considered mature. A MaMIMO system typically comprise one base station (BS) with several hundreds of antennas and a number of single antenna user terminals. The downlink of a MaMIMO system functions as follows: (1) The users transmit training symbols to the BS; each user consumes one time-frequency resource. (2) Relying on channel reciprocity, the BS estimates the channels to the users. (3) The BS transmits data to the users, typcially via a linear beamforming scheme.

The benefits - which all stem from the large number of antennas - with a MaMIMO system include: unprecedented energy efficiency, the ability to multiplex a large number os users simultaneously, and simple processing both at user terminals and at the BS. However, a number of issues arise,

- The pilot contamination problem. During the training phase (1), users of neighboring cells transmit training symbols to their BSs. The BS of the serving cell will overhear this training, and as a conseqeunce, beamform parts of its signal to those users during phase (3).
- Limited to TDD mode operation. Due to the large number of antennas at the BS, training signals must be sent from the user terminals and the downlink transmission phase must rely on channel reciprocity. However, many systems are today implemented as frequency-division-duplex (FDD) systems. Currently MaMIMO can therefore not easily by implemented for FDD-based systems. However, recent attempts are available [2].

- The training phase is consuming a large fraction of the available time-frequency resources.

Much research has been devoted to dealing with these issues but, to the best of the applicants knowledge, the approach we will take has not been researched before.

2.2 Physical Layer Security

PLS is based on the following result [3]. Consider a three-node-network in which a BS sends a signal to a legitime user (LU) in the presence of an eavesdropper (ED). Assume that the channel capacities between the BS and the LU and the ED are C_{LU} and C_{ED}, respectively. Then, a rate $C_{\text{PLS}} = \max(C_{\text{LU}} - C_{\text{ED}}, 0)$ can be transmitted to the LU perfectly secure even in the absence of a formal cryptographic system.

PLS is especially promising when combined with MaMIMO due to the recent observation that as the number of antennas grows large, *a passive ED is not harmful in the sense that*

$$\lim_{\#\text{Antennas}\to\infty} \frac{C_{\text{PLS}}}{C_{\text{LU}}} = 1.$$

As a countermeasure, the ED may seek to fool the BS to beamform the signal intended to the LU to the ED instead. The ED can accomplished this by transmitting a signal that overlaps in time and frequency with the training signal sent from the LU. The channel estimated by the BS is now polluted by the channel to the ED. As a consequence, the BS will beamform signal to the ED and thereby generating a very low value of C_{PLS}. Even worse is that the BS and the LU does not know that signal has been beamformed to the ED, and will therefore continue their, now unsecure, communication.

Some rudimentary methods to detect the presence of an active ED are presented in [4, 5]. The same method that is foreseen to be capable of dealing with the limitations of MaMIMO given in Section 2.1 has also bearing on the detection of active EDs, as will be discussed in Section 3.4. An overview of PLS within MaMIMO can be found in [**?**]

2.3 The Channel Database

Since accurate and reliable positioning of user terminals is today possible to acquire [6], it has been suggested [7] to construct a database containing the received signal strength (RSS) at the BS from a user that is positioned at a certain location. To build and maintain the database, advanced machine learning algorithms are clearly needed. Such a database enables a multitude of possibilities. For example, the scheduling and power control of users are improved; the users need to report their locations (or alternatively, the BS is responsible for estimating the user locations), then the BS requests RSS information for the users from the database, and finally schedules the users and assigns transmit powers to them.

2.4 Radio Channel Propagation Characteristics

Propagation aspects of wireless radio channels are today well understood and sophisticated channel models, such as the COST2100 model [8], have been developed. The transmitted signal from a user terminal propagates to the BS via a set of reflecting objects, termed clusters. A cluster is really a collection of reflection points that are so closely spaced so that the antenna array does not have sufficient resolution to resolve them individually. A MaMIMO antenna array has high spatial resolution and can therefore resolve reflection points into well-localized clusters. For the BS, the implication is that the radio signal is received from a set of well defined angles, the so called angle of arrivals (AoA). A further important result of radio propagation for MaMIMO is that clusters are typically only visible at parts of the antenna array [9]. In line-of-sight (LOS) conditions, besides reaching the antenna array via a set of clusters, there is also a direct path for the radio wave from the user to the BS.

3 Project Description

The basic scenario we consider is one where a BS is transmitting downlink data to a set of K user terminals. The number of antenna elements at the BS is M. Further, we will assume that the BS knows the physical locations of the K users. The project aims at utilizing this location information for MaMIMO is the most beneficial way. Before going through the project in detail, we first lay down the envisioned system in Section 3.1. Detailed information on the sub-tasks and their durations is provided in Sections 3.1 - 3.5.

3.1 Envisioned System

Assume that the K users establish their physical location and report this to the BS; alternatively, the BS estimates the users's locations. The BS requests the Angles-of-departures (AoD) to reach the locations of the users from a central node termed the Channel Cluster Database (CCD); the CCD also provides the BS with the path-loss for each AoD. Notice that the AoDs to reach the users are simply the AoAs of the uplink.

The information from the CCD will now be utilized in the following three ways.

- To implement a space-division-multiple-access scheme. Given the AoDs and their corresponding path-losses, the BS can spatially multiplex the K users by identifying a set of AoDs so that all users are reached, and no selected AoD reaches two scheduled users. The probability for successfully doing so was recently analyzed and shows that users has with high probability a cluster that is not shared with any other user [10].
  Example. Assume that there are 7 users in the system positioned at positions A-G, respectively. The BS requests AoD information from the CCD and obtains the information shown in Table 1. In this case, there are 8 AoDs (a-h) that reach the 7 users. We can see that the user at location B cannot be reached without causing interference to user location A. Therefore, we cannot schedule the user at B. Since B is not scheduled, the BS chooses AoD a to reach A since this AoD has the smallest path loss. In a similar fashion, we can see that users at locations C,D, and E cannot be simultaneously served. Suppose that we choose to serve C and D. Then the BS selects the AoDs c and e. The two users at locations F and G cannot be simultaneously reached either; if we choose to serve G, then we transmit in the AoD f since it has the smallest path loss. In this example, 4 of the 7 users was scheduled.

User location	AoD	Path Loss
A	a	-5 dB
	b	-10 dB
	h	-12 dB
B	a	-12 dB
	b	-20 dB
C	c	-3 dB
	d	7 dB
D	d	-5 dB
	e	-8 dB
E	e	-6 dB
F	f	-8 dB
G	f	-6 dB
	g	-9 dB

We point out that it is indeed possible to schedule all 7 users simultaneously by requesting the users to send training signals, and then spatially separate them by means of standard techniques (e.g. zero-forcing). The benefit of the CCD is that the three user-groups (A,B), (C,D,E), and (F,G) can send overlapping training signals because the BS knows the AoAs. Therefore, if A and C transmit overlapping training, then the BS chooses to look in the AoAs a,b,h to obtain a channel estimate for A, while it looks in the AoAs c and d for C. This heavily reduces the overhead due to training signals.

- Another advantadge of the CCD is that the potential of PLS is drastically improved. As discussed in Section 2.2, the problem of PLS implemention boils down into the problem of detecting active EDs in MaMIMO. Recall that for PLS in MaMIMO there must be a training phase so that the BS can coherently beamform the signal to the the LU. Under the assumption that the BS knows the location of the LU, if the BS observes an AoA that does match with the database entry for the LU's location, then this may indicate an active ED. However, the transmission does not need to be halted because the BS can transmit only in the AoDs that corresponds to the LU. The net result is that with a CCD, also active EDs can be made harmless.
- The third issue to be dealt with via the CCD is the pilot contamination problem, and more generally interference avoidance. If the BS knows the locations, and thereby the AoAs, of the users, then there is no need to beamform signal energy in any other directions. It can be foreseen that the pilot contamination problem in MaMIMO can be almost entirely eliminated. This is so since the radio waves between a BS and a user in a neighboring cell are typically reflected by objects that has LOS to the BS in the close vicinity of the user. This means that users in neighboring cells do not share clusters to any large extent, unless they are at the cell edges. However, cell edge users can be scheduled in different time-frequency resources.

3.2 WP1: Research related to the propagation environment

The CCD can keep track of the clusters that are stable over time. Clusters that are rapidly changing, for example generated by reflections on trucks, cars etc cannot easily be a part of the CCD[1]. Rather,

[1] We will discuss inclusion of rapidly changing clusters later in conjunction with Figure 1.

the CCD entries must consist of reflections on stationary non-movable objects. Sophisticated cluster-based models exist for conventional MIMO, for example the COST2100 model, but they are not developed for MaMIMO. Attempts to refine the COST2100 model into MaMIMO are ongoing both in academia and in industry. However, even in these refined models there are open questions that must be tackled for successful implementation of the CCD. The main question is the stability of the clusters. In earlier models the number of clusters is a random variable, and the "'channel modelling"' essentially boils down into proposing parameters for the random variable. Not much attention is put towards the life-time of the clusters, path-loss stability, how many clusters that are stationary vs. temporary, and how many of the stationary clusters that are shared among different locations in space.

In order to answer these question, we aim at re-evaluating measured data from earlier measurement campaigns as well as setting up a new measurement campaign. The new campaign will utilize Lund University's testbed for MaMIMO and take place during the course of several days. The testbed consists of a 100 antenna BS and ten single antenna users. The BS is likely to be placed on the roof of the EE-building of Lund University and then a number of persons[2] will be equipped with single antenna terminals and walk randomly around the campus for several hours per day, both early in the morning, mid-day, afternoon, and in the evening. This campaign will generate a vast amount of data, from which entirely new MaMIMO propagation properties can be extracted. In particular it will allow us to establish the stationary part of the propagation channel that can constitute the CCD. Clearly, different environments exhibit different richness in its stationary clusters. Therefore, we intend to repeat the campaign in downtown Lund later in the project. However, whether or not this will be necessary depends on the outcome of the first campaign.

3.3 WP2: Research related to machine learning of the CCD

In this work package the ambition is to build a supervised machine learning algorithm that observes the training signals from users at different time and physical locations, constructs and maintains a database of visible clusters for each physical location, and predicts the visible clusters and their strengths for any location not in the database and/or a location that has not been observed for a long time. Construction and maintenence of such a database is similar to the problem surveyed in [7], with the important difference that we here work at a cluster level and not only at a signal strength level. For this WP, the measurement campaign from WP1 is of uttermost importance. As the campaign stretches over several days and involves several users, we have a vast set of measurement points so that we can rigorously cross-validate the machine learning mechanism. We do not foresee the development of any radically new machine learning algorithms; rather we will tailor existing methods such as discriminant analysis or support vector machines to our given scenario.

To mention a few of the open issues we face,

- Update mechanism of a cluster. Suppose that we have a database entry for location X at some time point T_0, and that we observe training signals at location Y at time T_1. Assume that the CCD entry for X does not match very well with the new observation. How should we update the CCD for location X? One can argue that these are two different locations, and may have different visible clusters and, consequently, do not update at all. One can also argue that there has been a change in the environment, so that the previous CCD entry at X is completely outdated and, consequently, replace it. Further, one can also argue that the CCD entry for X was noisy, and update it according to some rule.

[2]We intend to hire undergraduate students for this purpose.

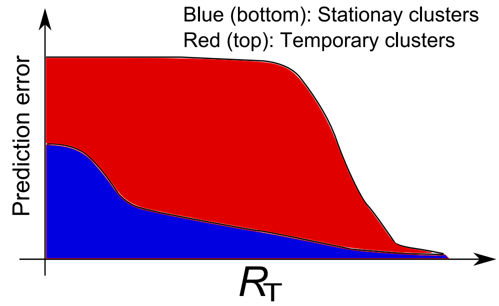

Figure 1: Schematic illustration of Prediction errors vs. training signals/sec/m^2. Top part is for the prediction of temporary clusters, while the bottom is for stationary clusters.

- The amount of training data. One ambition of the project is to avoid overhead in the form of training signals. Whether or not training signals must be sent frequently in order to maintain the CCD is an open question. It is natural to discuss the training signal rate per unit of area (unit: signals/sec/m^2); denote it by R_{T}. With a given value of R_{T} one can achieve a certain average prediction error of the visible clusters and their path-losses. The goal is clearly to develop a machine learing algorithm that will minimize the prediction error for a given R_{T}, however there is no previous research on the tradeoff between these two quantities. An outcome of the project may very well be that in order to obtain a reasonable prediction error, R_{T} must be unacceptably high, but given recent measurement campaigns [11–15] we expect that this is not the case.
- If there is a new, possibly temporary, cluster visible in some area, how many observations of it is needed in order to utilize it (i.e., include it into the CCD)? Moreover, how should the mechanism for spreading this cluster be made? With spreading it, we mean that if the cluster is initially observed at position X_1, and then again at close-by positions $X_2, X_3, \ldots, X_N$ within some reasonable time-period, this cluster should be put into the CCD at other nearby locations as well. A similar question is that if a given cluster is visible at locations $X_1, \ldots, X_N$, but from training signals we can see that it is no longer visible at locations near $X_1, \ldots, X_M, M < N$, then should we remove it from $X_{M+1}, \ldots, X_N$?

In Figure 1 we schematically illustrate the potential outcome of the machine learning WP. If we try to include only the stationary clusters[3] the fraction of training may be fairly low while for the temporary clusters, it seems reasonable that we must at least monitor the environment at a rate that matches the changes in the clusters. We point out again, that in contemporary literature, there are no attempts to build a CCD so therefore Figure 1 is merely representing our expectations of the outcome.

3.4 WP3: Application to Cellular MaMIMO Systems and COMP

A CCD opens up a wide array of opportunites and below we mention the aspects for system design that we intend to work on within the project

- Assume no BS coordination (i.e., no COMP) and a MaMIMO antenna in the cell center. In the system there are K users requesting service and the BS knows their locations. The

[3] Also the stationary clusters show some random variations in their path-losses, and can be obstructed at parts of the course of the day. This explains why repeated training is needed at all for stationary clusters.

problem to be dealt with is to schedule these K users over space, time, and frequency. In a fashion similar to the discussed example in Section 3.1, we seek to develop an algorithm that spatially multiplex as many users as possible onto the same time-frequency resource while at the same time guaranteeing that no spatially multiplexed users are sharing any clusters. As K grows and the environment is rich so that there are a multiple visible clusters at each location, the dimensionality of the scheduling problems grows which calls for the development of low-complexity scheduling methods.

- The system can be made more efficient if we allow small groups of users to share the same cluster, but use beamforming techniques to spatially separate the users within the groups. Beamforming requires the users to send orthogonal training signals so that instantaneous channel estimates are facilitated. However, users that belong to different groups can send overlapping training signals since they do not share any clustes and can therefore be resolved at the BS side. This greatly reduces the overhead due to training. However, the scheduling problem at the BS complicates. For a given size of the group size we aim at developing a low-complexity scheduling algorithm that maximizes the spectral efficiency.

- In a system design where downlink transmission relies on the CCD there is very little pilot contamination. The reason is that given the user location there is no need to transmit any training signals. However, pilot contamination is caused by training signals, thus, there cannot be any pilot contamination since there is no training. However, for two users in different cells that are on the cell edge close to each other, it is likely that the clusters to these two users are the same. In a COMP setting this problem can be alleviated. If the BSs are interconnected via a backhaul network, and BSs have location information of their respective users, then one can ensure that two users that are physically close are not multiplexed over the same time-frequency resource. Alternatively, the BSs can request orthogonal training signals from close-by cell edge users. Altogether, with appropriate CCD-enhanced system design, there is good hope that the problem of pilot contamination can be almost entirely eliminated.

3.5 WP4: Application to PLS

As already discussed, the CCD can be utilized to detect active eavesdroppers and thereby improve PLS (physical layer security) properties. We shall assume a sitation where the user can securely communicate its location to the BS - this can for example be made under the security that PLS offers. The user is now transmitting a training signal to the BS. With a CCD, the BS can compare the measured channel response from the user with the CCD entry. The BS cannot beamform in the direction of the channel response, since for all locations that share clusters with the user, an eavesdropper can overhear the transmission. Therefore, the BS removes the directions predicted by the CCD from the channel response, and beamforms in the direction of what remains - this is the instantaneous direction. An eavesdropper that is not positioned very close to the user cannot overhear this transmission.

As a remedy, the eavesdropper transmits a training signal of its own that overlaps with the one sent from the user. If this signal goes undetected by the BS, then the signal will be partly beamformed to the eavesdropper and the transmission is not secure. However, with a CCD the situation is improved. If the incoming signal to the BS during the training phase is from directions that do not coincide with the directions predicted by the CCD, the BS can declare an attack and terminate the transmission. However, it is an open question how well this detection scheme will work in practice and also how large role normal intercell-interference will play. This WP aims at researching the usefulness of the CCD within a PLS MaMIMO context.

4 Significance

A weakness of traditional MaMIMO systems is that they usually operate in TDD model. However, contemporary systems are mostly FDD based. This project aims at relaxing the TDD mode operation of MaMIMO into arbitrary operation. Therefore the project is of high economical value for Swedish industry. Further, the research of BSs that can learn its environment, and thereby integrate many different technologies within the same framework, is a new direction within wireless communications and is an interesting, timely, and very relevant research field on its own right.

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Interdisciplinarity

My application is interdisciplinary

☐

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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	Fredrik Rusek	10
2	Participating researcher	Doktorand	85

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	2019	Total
1	Applicant	Fredrik Rusek	10	139,284	142,770	146,340	149,990	578,384
2	Participating researcher	Doktorand	85	647,802	664,000	680,600	697,610	2,690,012
	Total			787,086	806,770	826,940	847,600	3,268,396

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

Running Costs

	Running Cost	Description	2016	2017	2018	2019	Total
1	Datorer	Laptop	10,000	0	0	0	10,000
2	Resor	Konferensresor	50,000	50,000	50,000	50,000	200,000
3	Lön: testpersonal	10 personer, 20 timmar/person, 300 kr/timme	60,000				60,000
	Total		120,000	50,000	50,000	50,000	270,000

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	787,086	806,770	826,940	847,600	3,268,396		3,268,396
Running costs	120,000	50,000	50,000	50,000	270,000		270,000
Depreciation costs					0		0
Premises					0		0
Subtotal	907,086	856,770	876,940	897,600	3,538,396	0	3,538,396
Indirect costs					0		0
Total project cost	907,086	856,770	876,940	897,600	3,538,396	0	3,538,396

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

I projektet deltar Fredrik Rusek (10%) samt en doktorand på (85%). En årlig löneökning på 2.5% har antagits. Löner är inklusive OH och sociala avgifter.

I projektet skall en större mätkampanj genomföras och jag planerer anställa 10 masterstudenter på 20 timmar var. Beräknad kostnad är 300/timme.

Other funding

Describe your other project funding for the project period (applied for or granted) aside from that which you apply for from the Swedish Research Council. Write the whole sum, not thousands of SEK.

Other funding for this project

Funder	Applicant/project leader	Type of grant	Reg no or equiv.	2016	2017	2018	2019

CV and publications

CV

Curriculum Vitae for Fredrik Rusek

Personal data

Born:	11 April 1978 in Lund, Sweden
Nationality:	Swedish
Address:	Anders Sassers väg 25
	24135 Eslöv, Sweden
Tel. (home):	+46 413 10644
Tel. (Office):	+46 46 2224940
Email:	fredrik.rusek@eit.lth.se

1. Undergraduate degree: Master of Science in Electrical Engineering from Lund University. Completed January 15, 2003.

2. Doctoral exam: Completed September 24, 2007; area: digital communications; title: "Partial response and faster-than-Nyquist signaling"; supervisor: Professor John B. Anderson; opponent: Professor Joachim Hagenauer, Technical University of Munich (TUM).

3. Post-doctor visits: I was guest researcher for three weeks at the Hong Kong University of Science and Technology (HKUST) in November 2007. I was invited by Professor Wai-Ho Mow.

4. Docent competence: I became Docent in 2012.

5. Current employment: Associate professor in communication theory at Lund University.

6. Previous employment: 2003-2007, Ph.D. student at Lund University. Oct. 2007 - March 2008, Researcher at Lund University. March 2008 - June 2012, Assistant Professor at Lund University. June 2012 - March 2014, Algorithm Expert at Huawei Technologies in Lund, Sweden.

7. Supervision of Ph.D. students: I am/was secondary supervisor for seven PhD students. Four of them have finished with a Ph.D. degree and one finished after obtaining a licentiate degree,

- Deepak Dasalukunte, Ph.D. degree obtained January, 2012.
- Peter Hammarberg, Ph.D. degree obtained February, 2012.
- Dzevdan Kapetanovic, Ph.D. degree obtained September, 2012.
- Adnan Prlja, Ph.D. degree obtained March, 2013.
- Farzad Foroughi Abari, Licentiate degree obtained November, 2011.

Student number 6 got health problems and needed to quit his Ph.D. education. The last Ph.D student to which I am secondary advisor will finish during 2015. Currently, I serve as main advisor for one Ph.D student (Sha Hu). Sha started his Ph.D. studies in March 2015.
In addition, I have supervised around 30 master thesis students.

8. Interruption of research: 9 months parental leave, spread over several years. June 2012 - December 2014, Worked at Huawei at 40-80% load, non-research oriented tasks.

9. Other: During April 2012 - June 2013 I was program director for the International Master Program in Wireless Communications at Lund University.
Biography

Fredrik Rusek was born in Lund, Sweden on April 11, 1978. He received the Master of Science degree in electrical engineering in December 2002 and the Ph.D. degree in digital communication theory in September 2007, both from Lund Institute of Technology. Between October 2007 and March 2008 he held a research position within the SSF strategic center for high speed wireless communications at the department of electrical and information technology, Lund Institute of Technology. Between 2008 and 2012 he was an assistant professor at the same department. In June 2012, he was promoted to associate professor, but left to Huawei Technologies for an algorithm expert position. Since January 2015, he has resumed his associate professorship.
His research interests include modulation theory, coding theory, wireless communications, applied information theory and receiver design.

Fredrik is living together with Eva and their three children Julia, 14, Jonathan, 11, and Noel, 3, in Eslöv. He is a dedicated scubadiver in his spare time.

Publication list

List of Publications

Refereed Journal Papers: Published/Accepted

1. F. Rusek and J.B. Anderson. "Non binary and precoded faster-than-Nyquist signaling,", *IEEE Transactions on Communications*, vol. 56, no. 5, pp. 808-817, May, 2008.

2. F. Rusek and M. Lóncar. "On reduced-complexity equalization based on Ungerboeck and Forney observation models," *IEEE Transactions on Signal Processing*, vol. 56, no. 8, pp. 3784-3789, August 2008.

3. F. Rusek and J.B. Anderson. "Constrained capacity of faster-than-Nyquist signaling," *IEEE Transactions on Information Theory*, vol. 55, no. 2, pp. 764-775, Feb. 2009.

4. F. Rusek and J.B. Anderson. "Multistream faster-than-Nyquist signaling," *IEEE Transactions on Communications*, vol. 57, no. 5, May, 2009.

5. F. Rusek "On the existence of the Mazo-limit on MIMO channels," *IEEE Transactions on Wireless Communications*, vol. 8, no. 3, pp. 1118-1121, March, 2009.

6. D. Dasalukunte, F. Rusek, and V. Öwall "Multicarrier faster-than-Nyquist transceivers: hardware architecture and performance analysis", *IEEE Trans. Circuits and Systems*, vol 58, no. 4, Apr. 2011

7. F. Rusek, E. Au, W. H. Mow and J.B. Anderson "A minimum distance analysis of multihead-multitrack magnetic recording channels," *IEEE Transactions on Information Theory*, vol. 58, no. 2, pp. 878 - 887, Feb. 2012.

8. D. Kapetanovic and F. Rusek "The effect of signaling rate on capacity for linear transmission systems," *IEEE Transactions on Communications*, vol. 60, no. 2, pp. 421 - 428, Feb., 2012.

9. P. Hammarberg, F. Rusek, and O. Edfors "Overview of channel estimation algorithms for OFDM-IDMA: Complexity and performance," To appear *IEEE Transactions on Wireless Communications*, 2012.

10. P. Hammarberg, F. Rusek, and O. Edfors "Iterative receivers with channel estimation for multi-user MIMO-OFDM: Complexity and performance," *EURASIP Journal on Wireless Communications and Networking*, no. 3, Mar. 2012.

11. F. Rusek, A. Lozano, N. Jindal 'Mutual Information of IID Complex Gaussian Signals on Block Rayleigh-faded Channels," *IEEE Transactions on Information Theory*, vol. 58, no. 1, pp. 331-340, Jan. 2012.

12. F. Rusek "Achievable rates of IID Gaussians on the non-coherent block-fading channel without channel distribution knowledge at the receiver," *IEEE Transactions on Wireless Communications*, no. 4, Apr. 2012.

13. F. Rusek and D. Fertonani "Bounds on the information rate of intersymbol interference channels based on the Ungerboeck observation model," *IEEE Transactions on Information Theory*, vol. 58, no. 3, pp. 1470-1482, Mar., 2012.

14. F. Rusek and A. Prlja "Optimal channel shortening for MIMO and ISI channels," *IEEE Transactions on Wireless Communications*, vol. 11, no. 2, pp. 810-818, Feb., 2012.

15. * F. Rusek, D. Persson, B. K. Lau, E.G. Larsson, T.L. Marzetta, O. Edfors, and F. Tufvesson "Scaling up MIMO: Opportunities and challenges with very large arrays," *IEEE Signal Processing Magazine*, Vol. 30, No. 1, pp. 40-60, 2013.

16. D. Kapetanović, F. Rusek, T. E. Abrudan, and V. Koivunen "Optimal minimum Euclidean distance MIMO precoders and their lattice classifications," *IEEE Transactions on Signal Processing*, 2012.

17. J. B. Anderson and F. Rusek "Faster than Nyquist signaling," *Proceedings of the IEEE*, Feb. 2012.

18. G. Colavolpe, A. Modenini, and F. Rusek "Channel Shortening for Nonlinear Satellite Channels", *IEEE Communications Letters*, vol. 16, No. 12, Dec. 2012.

19. D. Dasalukunte, F. Rusek, and V. Öwall, "A 0.8mm2 9.6mW Iterative Decoder for Faster-than-Nyquist and Orthogonal Signaling Multicarrier Systems in 65nm CMOS," *IEEE Journal of Solid State Circuits*, 2013.

20. A. Modenini, F. Rusek, and G. Colavolpe, "Optimal transmit filters for ISI channels under channel shortening detection", *IEEE Transactions on Communications*, vol. 61, pp. 4997-5005, Dec. 2013.

21. D. Kapetanović, H. V. Cheng, W. H. Mow, and F. Rusek "Optimal two-dimensional lattices for MIMO precoding," *IEEE Transactions on Wireless Communications*, Vol. 12, No. 5, pp. 2104-2113, 2013.

22. F. Rusek, G. Colavolpe, and C.E. Sundberg, ”40 years with the Ungerboeck model: Overlooked opportunities,” *IEEE Signal Processing Magazine*, May 2015

23. * X. Gao, O. Edfors, F. Rusek, F. Tufvesson, ”‘Massive MIMO performance evaluation based on measured propagation data”’ Accepted for publication in *IEEE Transactions on Wireless Communications,* Feb. 2015. Also available at arXiv:1403.3376.

24. * G. Dahman, F. Rusek, M. Zhu, and F. Tufvesson, ”‘On the Probability of Non-Shared Multipath Clusters in Cellular Networks”’ Accepted for publication in *IEEE Wireless Communications Letters*, Feb. 2015.

25. * D. Kapetanović, G. Zheng, and F. Rusek, ”‘Physical Layer Security for Massive MIMO: An Overview on Passive Eavesdropping and Active Attacks”’, Accepted for publication in *IEEE Communications Magazine* Special Issue on Physical Layer Communications, June 2015. Pre-pring available upon request.

26. D. Kapetanović, H. V. Cheng, W. H. Mow, and F. Rusek, ”‘Lattice Structures of Precoders Maximizing the Minimum Distance in Linear Channels.”’ *IEEE Transactions on Information Theory* vol. 61, no. 2, pp. 908-916, Feb. 2015.

27. P. Banelli, S. Buzzi, G. Colavolpe, A. Modenini, F. Rusek, A. Ugolini, ”‘Modulation Formats and Waveforms for 5G Networks: Who Will Be the Heir of OFDM?”’ *IEEE Signal Processing Magazine*, Vol. 31, No. 6, pp. 80-93, 2014

Journal papers in submission

28. F. Rusek and O. Edfors, “An information theoretic characterization of channel shortening receivers,” in submission *IEEE Transactions on Information Theory.* Also available on Arxiv: 1402.7258.pdf

29. F. Rusek and B. Endah Priyanto, ”‘Reduced basis maximum likelihood pilot based fractional frequency offset estimation with applications to LTE,”’ In submission *IEEE Signal Processing Letters.*

Refereed Conference Papers

30. F. Rusek and J.B. Anderson. “M-ary coded modulation by Butterworth filtering,” in *Proc. IEEE International Symposium on Information Theory (ISIT)*, Yokohama, June 2003.

31. F. Rusek and J.B. Anderson. “Coded optimal partial response signaling,” in *Proc. IEEE International Symposium on Information Theory (ISIT)*, Chicago, June 2004.

32. F. Rusek and J.B. Anderson. "On coded and multidimensional partial response signaling," in *Proc. IEEE International Symposium on Information Theory and its Applications (ISITA)*, Parma, Oct. 2004.

33. J.B. Anderson and F. Rusek. "The Shannon bit error limit for linear coded modulation," in *Proc. IEEE International Symposium on Information Theory and its Applications (ISITA)*, Parma, Oct. 2004.

34. F. Rusek and J.B. Anderson. "On decision depth for partial response codes," in *Proc. IEEE International Conference on Communications (ICC)*, Seoul, May 2005.

35. F. Rusek and J.B. Anderson. "Near BER optimal partial response signaling," in *Proc. IEEE International Symposium on Information Theory (ISIT)*, Adelaide, Sept. 2005.

36. F. Rusek and J.B. Anderson. "The two-dimensional Mazo limit," in *Proc. IEEE International Symposium on Information Theory (ISIT)*, Adelaide, Sept. 2005.

37. J.B. Anderson and F. Rusek. "Improving OFDM: Multistream faster-than-Nyquist signaling," *In Proc. IEEE 6th International ITG-Conference on Source and Channel Coding*, Munich, April 2006.

38. F. Rusek and J.B. Anderson. "Successive interference cancellation in multistream faster-than-Nyquist signaling," in *Proc. ACM/IEEE International Wireless Communications and Mobile Computing Conference (IWCMC)*, Vancouver, July 2006.

39. F. Rusek and J.B. Anderson. "Serial and parallel concatenations based on faster-than-Nyquist signaling," in *Proc. IEEE International Symposium in Information Theory (ISIT)*, Seattle, pp. 970–974, July 2006.

40. F. Rusek and J.B. Anderson. "On information rates of faster-than-Nyquist signaling," in *Proc., IEEE Global Communications Conference (Globecom)*, San Francisco, Nov. 2006.

41. F. Rusek. "A first encounter with faster-than-Nyquist signaling over the MIMO channel", in *Proc. IEEE Wireless Communication and Networking Conference (WCNC)*, Hong Kong, March 2007.

42. F. Rusek and J.B. Anderson. "Maximal capacity partial response signaling," in *Proc. International Conference on Communications (ICC)*, Glasgow, June 2007.

43. J.B. Anderson and F. Rusek. "Optimal side lobes under linear and faster-than-Nyquist modulation," in *Proc. International Symposium on Information Theory (ISIT)*, Nice, June 2007.

44. F. Rusek, A. Prlja and M. Lóncar. "A comparison of Ungerboeck and Forney models for reduced-complexity ISI equalization," in *Proc. IEEE Global Communications Conference 2007 (Globecom)*, Nov. 2007.

45. F. Rusek and D. Kapetanović. "Optimal time–frequency occupancy of finite packet OFDM," in *Proc. IEEE Personal, Indoor and Mobile Radio Conference 2007 (PIMRC)*, Sept. 2007.

46. F. Rusek, E. Au, J. B. Anderson, W. H. Mow "A minimum distance analysis of a certain class of two dimensional ISI channels," in *Proc. International Symposium on Information Theory (ISIT)*, Toronto, July 2008.

47. A. Prlja, J.B. Anderson and F. Rusek "Receivers for faster-than-Nyquist signaling with and without turbo equalization," in *Proc. International Symposium on Information Theory (ISIT)*, Toronto, July 2008.

48. F. Rusek and D. Kapetanović "The effect of symbol rate on constrained capacity for linear modulation," in *Proc. International Symposium on Information Theory (ISIT)*, Toronto, July 2008.

49. F. Rusek, A. Prlja and D. Kapetanović "Faster-than-Nyquist signaling based on short finite pulses," Radiovetenskaplig konferens 2008 (RVK'08), Växjö, Sweden.

50. F. Rusek and D. Kapetanović "Design of close to optimal Euclidean distance MIMO-precoders," in *Proc. International Symposium on Information Theory (ISIT)*, Seoul, June/July 2009.

51. A. Prlja, J.B. Anderson and F. Rusek "New reduced state space BCJR algorithms for the ISI channel," in *Proc. International Symposium on Information Theory (ISIT)*, Seoul, June/July 2009.

52. F. Rusek and D. Fertonani "Lower bounds on the information rate of intersymbol interference channels based on the Ungerboeck observation model," in *Proc. International Symposium on Information Theory (ISIT)*, Seoul, June/July 2009.

53. D. Dasalukunte, F. Rusek, V. öwall and J.B. Anderson 'Transmitter architecture for faster-than-Nyquist signaling systems," in *Proc. International Symposium on Circuits and Systems (ISCAS)*, Taipei, May, 2009.

54. P. Hammarberg, F. Rusek, P. Salvo-Rossi and O. Edfors "Evaluation of an iterative receiver for multi-user, multi-antenna OFDM system using EXIT charts," in *Proc. IEEE Global Communications Conference 2009 (Globecom)*, Hawaii, Nov. 2009.

55. D. Dasalukunte, F. Rusek, V. öwall, K. Ananthanarayanan, and M. Kandasarny, "Hardware implementation of mapper for faster-than-Nyquist signaling transmitter", in *Proc NORCHIP 2009*, Trondheim, Norway, Nov. 2009.

56. D. Dasalukunte, F. Rusek and V. öwall, "An iterative decoder for OFDM based faster-than-Nyquist signaling receivers", in *Proc. International Conference on Communications (ICC)*, Cape Town, SA, May 2010.

57. F. Hug and F. Rusek, "The BEAST for Maximum-Likelihood Detection in Non-Coherent MIMO Wireless Systems", in *Proc. International Conference on Communications (ICC)*, Cape Town, SA, May 2010.

58. F. Rusek, "A Novel Soft-Input Soft-Output Reduced Complexity MIMO Trellis Detector", in *Proc. International Conference on Communications (ICC)*, Cape Town, SA, May 2010.

59. D. Kapetanović and F. Rusek, "On Precoder Design under Maximum-Likelihood Detection for Quasi-Stationary MIMO Channels", in *Proc. International Conference on Communications (ICC)*, Cape Town, SA, May 2010.

60. F. Rusek, A. Lozano and N. Jindal, "Mutual Information of IID Complex Gaussian Signals on Block Rayleigh-faded Channels", in *Proc. International Symposium on Information Theory (ISIT)*, Austin, TX, June 2010.

61. D. Kapetanović and F. Rusek, "'A Comparison Between Unitary and Non-Unitary Precoder Design for MIMO Channels with MMSE Detection and Limited Feedback", In *Proc. IEEE Global Communications Conference 2009 (Globecom)*, Miami, FL, Dec. 2010.

62. D. Kapetanović and F. Rusek, "Linear precoders for parallell Gaussian channels with low decoding complexity," In Proc. *IEEE Vehicular Technology Conference-Fall*, San Francisco, Sept. 2011.

63. X. Gao, O. Edfors, F. Rusek, and F. Tufvesson "Linear pre-coding performance in measured very-large MIMO channels" In Proc. *IEEE Vehicular Technology Conference-Fall*, San Francisco, Sept. 2011.

64. D. Kapetanović, H. V. Cheng, W. H. Mow, and F. Rusek, "Optimal lattices for MIMO precoding," In Proc. *IEEE International Symposium on Information Theory*, St. Petersburg, Russia, July 2011.

65. D. Dasalukunte, F. Rusek, V. Öwall, "Improved memory architecture for multicarrier faster-than-Nyquist iterative decoder," In Proc. *IEEE Intl. Symp. on VLSI (ISVLSI)*, Chennai, India, July, 2011.

66. F. Foroughi Abari, F. Rusek, and O. Edfors “On coefficient memory co-optimization for channel estimation in a multi-standard environment (LTE and DVB-H)”, In Proc. *8th International Workshop on Multi-Carrier Systems & Solutions*, Herrsching, Germany, May 2011.

67. F. Rusek, O. Edfors, and F. Tufvesson “Indoor Multi-User MIMO: Measured User Orthogonality and Its Impact on the Choice of Coding,” In Proc. *European Conference on Antennas and Propagation*, Prague, Czech Republic, March, 2012.

68. F. Rusek, N. Al-Dhahir, and A. Gooma “Optimal channel shortening with feedback,” In Proc. *IEEE Global Communications Conference 2012 (Globecom)*, Anaheim, CA., Dec., 2012.

69. X. Gao, F. Tufvesson, O. Edfors, F. Rusek, ”Measured propagation characteristics for very-large MIMO at 2.6 GHz,” *The 46th Annual Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, California, USA, 2012.

70. H. Prabhu, J. Rodrigues, O. Edfors, F. Rusek, ”Approximative Matrix Inverse Computations for Very-large MIMO and Applications to Linear Precoding Systems,” In Proc, *WCNC*, Shanghai, China, 2013.

71. D. Dasalukunte, F. Rusek, V. Öwall, ”A 0.8mm2 9.6mW Implementation of a Multicarrier Faster-Than-Nyquist Signaling Iterative Decoder in 65nm CMOS,” In Proc. *38th European Solid State Circuits Conference (ESSCIRC)*, Bordeaux, France 2013.

72. A. Modenini, F. Rusek, G. Colavolpe, ”Optimal transmit filters for channel shortening receivers,” In Proc. *Intl Conference on Communications (ICC)*, Budapest, Hungary, May 2013.

73. B. Priyanto, F. Rusek, S. Kant, J. Chen, H. Sha, and C. Wugengshi ”Iterative interference cancellation and robust equalization for HETNETs,” In Proc. *IEEE Vehicular Technology Conference (VTC-fall)*, Las Vegas 2013.

74. H. Prabhu, O. Edfors, J. Rodrigues, L. Liu, F. Rusek, ”‘Hardware efficient approximative matrix inversion for linear pre-coding in massive MIMO,”’ In Proc. *IEEE International Symposium on Circuits and Systems (ISCAS)*, Melbourne, Australia, 2014.

75. H. Prabhu, O. Edfors, J. Rodrigues, L. Liu, F. Rusek, ”‘A low-complex peak-to-average power reduction scheme for OFDM based massive MIMO systems,”’ In Proc. *IEEE International Symposium on communications, control and signal processing*, Athens, Greece, 2014.

76. F. Rusek and O Edfors, "'An information theoretic characterization of channel shortening receivers,"' *The 47th Annual Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, California, USA, 2013.

77. S. Kant, F. Rusek, B. Priyanto,and H. Sha "A low-complexity 4x4 MIMO demodulator for LTE-A," *Proc. IEEE Personal, Indoor and Mobile Radio Conference (PIMRC)*, Washington D.C. 2014.

78. D. Kapetanovic, A. Al-Nahiri F. Rusek "Detection of the pilot contamination attack for the physical layer security of massive MIMO," *Proc. IEEE Personal, Indoor and Mobile Radio Conference (PIMRC)*, Washington D.C. 2014.

79. * S. Imtiaz, G. Dahman, F. Rusek, F. Tufvesson "Investigating the directional reciprocity of uplink and downlink channels in FDD systems at multipaths clusters level," *Proc. IEEE Personal, Indoor and Mobile Radio Conference (PIMRC)*, Washington D.C. 2014.

80. J. Vieira, F. Rusek, F. Tufvesson, "'Reciprocity calibration methods for Massive MIMO based on antenna coupling"' *IEEE Global Communications Conference 2012 (Globecom)*, Austin, TX, 2014.

81. A. Modenini, F. Rusek, and G. Colavolpe, "'Faster-than-Nyquist signaling for next generation communication architectures. *IEEE Eusipco* 2014.

82. J. Yu, J. Park, F. Rusek, B. Kudryashov, I. Bocharova, "'High Order Modulation in Faster-than-Nyquist Signaling Communication Systems"' *IEEE 80th Vehicular Technology Conference (VTC2014-Fall)*, Vancouver, Canada, 2014.

83. * X. Gao, M. Zhu, F. Rusek, F. Tufvesson, O. Edfors, "'Large antenna array and propagation environment interaction"' *The 48th Annual Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, California, US 2014.

84. H. Prabhu, F. Rusek, J. Rodrigues, O. Edfors, "'High Throughput Constant Envelope Pre-coder for Massive MIMO Systems,"' *IEEE International Symposium on Circuits and Systems (ISCAS)*, Lisbon, Portugal, 2015.

Submitted Conference Papers

85. S. Hu and F. Rusek, "'On the Design of Reduced State Demodulators with Interference Cancellation for Iterative Receivers"', Submitted to *IEEE International Symposium on Information Theory (ISIT)* Jan. 2015.

Books and book chapters

86. D. Dasalukunte, V. Öwall, F. Rusek, and J. B Anderson, "'Faster-than-Nyquist signaling transceivers,"' Springer-verlag. 2014.

87. D. Kapetanovic and F. Rusek, "'Precoding for linear channels"', in Future trends in Communications, CRC-press. Ed. Mario Marques. 2014.

Patents. All with Huawei Technologies. All filed by Huawei.

88. F. Rusek et al. *Robust Equalizer for a Receiver in a Heterogenous Network with Common Reference Signal Interference.* Filed 2012.
89. F. Rusek et al. *Iterative Pilot-Interference Cancellation for OFDM Systems.* Filed 2012.
90. F. Rusek et al. *Iterative Interference Rejective Combing.* Filed 2013.
91. F. Rusek et al. *Adaptive Low-Complexity Joint Iterative Channel Estimation and Decoding in MIMO-OFDM System.* Filed 2013.
92. F. Rusek et al. *Robust QRDM based detector for a Receiver in a Heterogenous Network with Common Reference Signal Interference.* Filed 2013.
93. F. Rusek et al. *A simple protocol to detect the pilot contamination attack for secrecy capacity of massive MIMO.* Filed 2013.
94. F. Rusek et al. *Optimal channel shortening of arbitrary linear channels for iterative receivers.* Filed 2013.
95. F. Rusek et al. *Reduced Space and Dimension Near-Optimal MIMO Detection Scheme.* Filed 2013.
96. F. Rusek et al. *A Quasi-ML Detector for Large MIMO Systems.* Filed 2013.
97. F. Rusek et al. *Karhunen Loeve based Maximum Likelihood estimation of frequency offsets in OFDM systems using pilots.* Filed 2013.
98. F. Rusek et al. *Method and Apparatus for Enhanced Slow Link Adaption in Wireless Communication Systems.* Filed 2013.
99. F. Rusek et al. *Frequency offset estimation with extended Nyquist frequency based on resampling.* Filed 2013.
100. F. Rusek et al. *Mutual Information Prediction techniques for CQI Reporting in LTE.* Filed 2014.
101. F. Rusek et al. *Channel estimation error aware MMSE receivers with iterative noise color updating.* Filed 2014.
102. F. Rusek et al. *A Low-Complexity Fully Parallelizable Channel Shortening Based MIMO Detector* . Filed 2014.

103. F. Rusek et al. *Interference Estimation with Blind Power Ratio and Transmission Mode Detection in LTE.* Filed 2014.

104. F. Rusek et al. *A Robust Frequency OFfset Estimator for Frequency Offsets in OFDM.* Filed 2014.

105. F. Rusek et al. *A Gradient Based Method for PMI Detection in LTE.* Filed 2014.

106. F. Rusek et al. *A Wake up Application Apparatus for Touch Screen Mobile Phones.* Filed 2014.

CV

Name: Fredrik Rusek	**Doctorial degree:** 2007-09-24
Birthdate: 19780411	**Academic title:** Docent
Gender: Male	**Employer:** No current employer

Research education

Dissertation title (swe)		
Dissertation title (en)		
Organisation	**Unit**	**Supervisor**
Lunds universitet, Sweden Sweden - Higher education Institutes	Elektro- och informationsteknik 107201	
Subject doctors degree	**ISSN/ISBN-number**	**Date doctoral exam**
20204. Telekommunikation		2007-09-24

Publications

Name: Fredrik Rusek	**Doctorial degree:** 2007-09-24
Birthdate: 19780411	**Academic title:** Docent
Gender: Male	**Employer:** No current employer

Rusek, Fredrik has not added any publications to the application.

Register

Terms and conditions

The application must be signed by the applicant as well as the authorised representative of the administrating organisation. The representative is normally the department head of the institution where the research is to be conducted, but may in some instances be e.g. the vice-chancellor. This is specified in the call for proposals.

The signature*from the applicant*confirms that:

- the information in the application is correct and according to the instructions form the Swedish Research Council
- any additional professional activities or commercial ties have been reported to the administrating organisation, and that no conflicts have arisen that would conflict with good research practice
- that the necessary permits and approvals are in place at the start of the project e.g. regarding ethical review.

The signature *from the administrating organisation* confirms that:

- the research, employment and equipment indicated will be accommodated in the institution during the time, and to the extent, described in the application
- the institution approves the cost-estimate in the application
- the research is conducted according to Swedish legislation.

The above-mentioned points must have been discussed between the parties before the representative of the administrating organisation approves and signs the application.

Project out lines are not signed by the administrating organisation. The administrating organisation only sign the application if the project outline is accepted for step two.

Applications with an organisation as applicant is automatically signed when the application is registered.