Application

2015-03-31

2015-05573	**Björnson, Emil**	**NT-14**

Information about applicant

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Information about application

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Subject area:

Project title (english): Optimized Design of Wireless Networks with Multiple Performance Metrics

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Classification code: 20203. Kommunikationssystem, 20205. Signalbehandling, 20204. Telekommunikation

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Funds applied for

Year:	2016	2017	2018	2019
Amount:	985,253	1,014,061	1,043,732	1,074,294

Descriptive data

Project info

Project title (Swedish)*

Optimerad design av trådlösa nätverk med flera prestandamått

Project title (English)*

Optimized Design of Wireless Networks with Multiple Performance Metrics

Abstract (English)*

Most real-life optimization problems have multiple conflicting objectives, and the design of wireless cellular networks is not an exception. While high peak data rates have been the predominating objective of contemporary networks, many alternative performance objectives have emerged in the preparation for the fifth generation (5G) wireless networks; for example, higher area throughput, more connected devices, and better energy efficiency. This calls for advanced optimization tools.

Conventionally, network utility optimization has been used to distribute the wireless transmission power between user devices (in time, frequency, and space) to maximize a single performance metric/objective. The purpose of this project is to advance the state-of-the-art in network utility optimization in two unique directions: 1) The network deployment and infrastructure is explicitly modeled and treated as optimization variables; 2) The existence of multiple performance objectives is acknowledged from the very beginning and the fundamental tradeoffs between them are derived mathematically. These advances are made possible by innovative system modeling, based on realistic hardware characteristics and stochastic geometry tools, as well as adoption of multi-objective optimization methodology that tackles the multiple performance objectives in a fully rigorous manner.

This project is carried out at Linköping University. The project leader is docent Emil Björnson and the research will be carried out together with a doctoral student. The project will provide important new algorithms for network optimization, manifest the fundamental tradeoffs between the performance metrics of prominent importance in future wireless networks, and provide analytical answers to several key design questions; for example, how dense the network deployments should be, to what extent the access points should coordinate their behavior, and how the hardware quality can be tailored to balance between data rates and energy efficiency. From a broader perspective, the goal of the project is to support both industry and academia by developing a theory for optimal deployment of dense and heterogeneous future wireless networks.

Popular scientific description (Swedish)*

Smarta telefoner och surfplattor har blivit naturliga arbets- och underhållningsapparater för många människor. Därför har efterfrågan och kraven på trådlös tillgång till internettjänster ökat kraftigt och förväntas fortsätta att öka under överskådlig framtid. För varje 1,5 år som går så fördubblas datatrafiken i teleoperatörernas nät. Därför måste näten ständigt utvecklas och förbättras. Abonnemang på trådlös datatrafik marknadsförs ofta med dess maximala datatakt, men denna levereras bara om användaren råkar vara nära en av operatörens basstationer och om det är få aktiva användare i nätet. Det finns många alternativa sätt att avgöra hur bra ett trådlöst nät är, exempelvis vilken datatakt som garanteras i medeltal, hur många användare som kan vara anslutna samtidigt och hur energieffektiv dataöverföring är. Det finns således många målsättningar att ta hänsyn till när mobilnäten utvecklas för framtiden.

Vi vet idag ganska väl hur de trådlösa signalerna ska fördelas i tid och rum för att uppnå höga datatakter och begränsa störningar mellan användare. Däremot vet vi mindre om hur infrastrukturdesignen påverkar näten, dvs. utplacerandet av basstationer, valet av hårdvara och koordineringen mellan stationerna. Det unika med det här projektet är dels att infrastrukturen optimeras matematiskt tillsammans med de fysiska datasignalerna och dels att flermålsoptimeringsmetoder används för att analysera och visualisera vilka avvägningar som finns mellan olika designmål (t.ex. höga datatakter och hög energieffektivitet). Den vetenskapliga utmaningen ligger dels i att modellera problemställningarna ur en matematisk synvinkel och dels i att de olika designmålen vanligtvis är motstridiga och därför måste vägas mot varandra. Till exempel kan en användare få hög datatakt ifall den utsända energin är väldigt hög, men detta leder till låg energieffektivitet (relativt lite data per mängd energi).
Flermålsoptimering är en metod för att studera och visualisera sådana avvägningar för att förstå hur de olika målen är sammankopplade.

Det övergripande målet med projektet är att använda metoder från flermålsoptimering för att undersöka hur trådlösa nät bör konstrueras för att uppnå såväl användarnas som teleoperatörernas framtida kravlistor.

Project period

Number of project years*

4

Calculated project time*

2016-01-01 - 2019-12-31

Deductible time

Deductible time

Cause	Months

Career age: 39

Career age is a description of the time from your first doctoral degree until the last day of the call. Your career age change if you have deductible time. Your career age is shown in months. For some calls there are restrictions in the career age.

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 > 20205. Signalbehandling 2. Teknik > 202. Elektroteknik och elektronik > 20204. Telekommunikation

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

Keyword 1*

Cellular networks

Keyword 2*

Optimization

Keyword 3*

Physical layer

Keyword 4

Keyword 5

Ethical considerations

Specify any ethical issues that the project (or equivalent) raises, and describe how they will be addressed in your research. Also indicate the specific considerations that might be relevant to your application.

Reporting of ethical considerations*

No ethical issues are foreseen.

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

Appendix A: Research Programme

Purpose and Aims

The wireless communication traffic has doubled every 2.5 years for over a century; an exponential growth rate referred to as Cooper's law. This incredible success story of wireless technology is expected to continue, driven by the proliferation of smartphones and tablets, as well as new innovative applications (e.g., internet-of-things and augmented reality). The well-reputed Cisco Visual Networking Index predicts that the data traffic will even double every 1.5 years in the foreseeable future [Cis], which is possible only if the wireless networks are continuously improved to accommodate more traffic. In addition, other non-traffic-related performance metrics (e.g., energy efficiency, deployment cost, and number of user devices) have gained traction in recent years, which makes the design of future networks fundamentally more difficult—there is no longer one dominating metric, but tradeoffs need to be made between multiple metrics.

This main purpose of this project is to optimize the design of wireless networks using mathematical analysis. Conventional network optimization has proved how to distribute the wireless transmit power between user devices (in time, frequency, and space) to maximize a single performance metric/objective. This project will advance the state-of-the-art in two unique directions: 1) The network deployment and infrastructure is explicitly modeled and treated as optimization variables; 2) The network optimization considers the existence of multiple performance objectives and proves the fundamental tradeoffs between them. These advances are made possible by innovative system modeling, based on hardware characteristics and stochastic geometry tools, as well as adoption of the mathematical methodology of multi-objective optimization theory to tackle the multiple performance objectives in a fully rigorous manner. From a broader perspective, the project goal is to support both industry and academia by developing a theory for optimal deployment of dense and heterogeneous future wireless networks.

Motivation: The evolution of wireless communication networks is driven by the dream of ubiquitous wireless connectivity: *Any data service should be instantly accessible everywhere.* We have moved closer to this wireless dream with each generation of cellular networks; first by delivering wireless access to voice communications, then by providing basic wireless data services, and recently by delivering a WiFi-like experience with wide-area coverage and user mobility management. The support for high data rates has been the main performance objective in recent years [TVZ11], as seen from the academic focus on maximizing the sum rate of canonical communication models (e.g., broadcast and multiple-access channels) and the efforts from standardization bodies to meet the peak rate requirements specified in IMT-Advanced. In contrast, a variety of performance objectives are put forward in the technological preparations for the next generation of wireless networks, which are expected to be deployed around 2020 and are generally referred to 5G systems. Although there are no formal 5G requirements, some rule-of-thumbs have been presented, for example in [Oss13]:

- Higher user data rates: 10–100 times higher average user rates (in bit/s) are expected.
- Higher area data rates: 1000 times higher average rates (in bit/s/km^2) are anticipated.
- More connected devices: With the respective increases in user and area rates, 10–100 times more devices can be accommodated simultaneously per unit area.
- Higher energy efficiency (EE): The user/data rates should be improved without increasing the energy consumption, thus up to 1000 times higher EE (in bit/Joule) is required.

Furthermore, a variety of network aspects are growing more heterogeneous:

- Heterogeneous networks: The combination of access points with different ranges, traffic load that varies over time/space, radio access technologies, and hardware capabilities makes the network optimization highly heterogeneous.
- Heterogeneous devices: The differences in functionality and hardware capability of user devices are expected to grow. Large handheld devices can, for example, achieve high data rates by spatial multiplexing using advanced signal processing techniques, while small sensors seek low data rates under extremely tight energy constraints.
- Heterogeneous service requirements: Some cyber-physical and safety applications require very fast response times, while best-effort delivery is fine for other types of data services. Similarly, certain multimedia applications have continuous quality-of-service requirements, while other services are bursty in nature.

There are apparently many different performance objectives to keep in mind when designing future wireless networks. Unfortunately, the different objectives cannot be treated separately because they are coupled; sometimes in a consistent fashion, but often in conflicting ways such that improvements in one objective lead to deterioration of other objectives. This is because the same network *resources* (e.g., time, frequency, space, power, hardware characteristics, and deployment) play key roles in all metrics/objectives, but in incompatible ways. For example, higher peak user rates can be achieved by using more power (which affects the EE), allocating more transmission resources to users with good channels (which means less uniform user experience), or making use of intricate signal processing algorithms (which increases the complexity of user devices). The existence of multiple performance objectives, instead of one, calls for new optimization techniques.

Aims: As motivated above, the main goal of this project is to study the design of wireless networks having multiple performance objectives. A suitable and novel way to tackle this problem is by *multi-objective optimization (MOO) theory*, which is a rigorous mathematical methodology for optimizing, computing, and visualizing the achievable operating points [Zad63, MA04, BDME08]. In particular, the method exposes the fundamental interactions between the conflicting objectives and supports the *decision maker*, who designs the network, to achieve satisfactory balance with respect to *all* the objectives. Unlike game theory, where there are many competing agents and each objective describes the satisfaction of one them, there is only one decision maker (e.g., a network operator) in the MOO methodology and all objectives are treated with equal relevance—to not inject any preconceptions into the design.

The multi-objective optimization methodology is a standard tool in many engineering and economic related fields, but have received little attention from the wireless communication community. The project leader has written the first textbook that brings these topics together [63]. This book considers how the transmission power can be distributed in space and among users to balance between network throughput and user fairness. In this project, the originality lies in that we go beyond classical network optimization by also optimizing the network infrastructure (e.g., deployment density, interaction between access points, and hardware characteristics) and by considering new performance metrics that are highly relevant in 5G networks and beyond—these metrics might not even be throughput-related as conventionally assumed; see Figures 3 and 4. The feasibility of applying MOO theory for comprehensive and well-informed design of wireless networks (e.g., in terms of finding the right number of active antennas and users per area unit) was established in our survey paper [64] in IEEE Signal Processing Magazine (Special Issue on Signal Processing for the 5G Revolution) from Nov. 2014. This is a new research direction that lies greatly unexplored and the project leader has currently a world-leading position in this field, which can be sustained through this project.

Survey of the Field

The main purpose of a wireless network is to transfer information wirelessly between access points and user devices. The network functionality is divided into layers, whereof this project mainly considers the resource management that takes place in the physical (PHY) layer and media access control (MAC) layer. The conventional approach to physical-layer system optimization is to design the wireless transmission to maximize a certain scalar *network utility function*, for a given set of access points (e.g., base stations) and user devices [Kel97, GNT06, PC06], [14]. A common problem formulation is that of maximizing the (weighted) sum of the users' data rates under constraints on the transmit power [WSS06, LDL11], [47]. The sum can also be replaced by a product of the data rates or the worst-user utility metric to provide a certain level of fairness between users that have strong channels (e.g., are close to an access point) and users with weak channel conditions. Alternatively, the objective can be to minimize the transmitted power under constraints on the data rates of each active user [RFLT98, BO01, CHLT08]. While these utility functions only consider the data rates, energy efficiency has arisen as an alternative utility function in recent years [CZXL11, ICJF12], [2].

In essence, the aforementioned network utility problems correspond to selecting one of the objectives listed under "Purpose and Aims" (e.g., high user rates) as the sole objective, while the other objectives are ignored or transformed into constraints. The inherent assumptions in this approach are: 1) the many conflicting objectives of the network can be condensed into only one scalar objective; and 2) it is known beforehand what are good values for the constraints related to the other objectives. This simple approach has led to many algorithmic breakthroughs and knowledge around the fundamental limits of communication performance, but provides little insight on the interplay between different objectives, such as peak/average user rates, area throughput, energy efficiency, number of connected devices, and deployment cost. The increasing heterogeneity (in terms of service requirements, device capabilities, etc.) makes it increasingly complicated, if not impossible, to specify the constraints in just one universal way.

Multi-Objective Optimization

Instead of heuristically assuming that one of the objectives is the sole objective, the rigorous approach is to recognize the existence of multiple objectives [Zad63]; let us call them $g_1(\mathbf{x}), g_2(\mathbf{x}), \ldots, g_M(\mathbf{x})$ where M is the number of objectives. In wireless communications, these objective functions can be the area throughput, the number of active users, the energy efficiency, etc. The available resources (e.g., time, frequency, space, power, hardware characteristics, and deployment) are modeled by a compact set $\mathcal{X} \subset \mathbb{R}^D$, which is called the *resource bundle* and has an arbitrary dimension D. Each vector $\mathbf{x} \in \mathcal{X}$ represents a feasible way of utilizing the network resources. The satisfaction of this resource utilization equals $g_m(\mathbf{x}) \in \mathbb{R}$ with respect to the mth objective function. A larger value corresponds to higher satisfaction.

A key assumption in MOO is that the M objectives are *not* ordered and therefore studied without any preconceptions—all doors are kept open. It is assumed to exist a *decision maker* that would like to design the network to maximize *all* the M objectives simultaneously:

$$\begin{aligned} \underset{\mathbf{x}}{\text{maximize}} \quad & [g_1(\mathbf{x}), g_2(\mathbf{x}), \ldots, g_M(\mathbf{x})]^T \\ \text{subject to} \quad & \mathbf{x} \in \mathcal{X} \end{aligned} \tag{1}$$

where the utility is a vector $[g_1(\mathbf{x}), g_2(\mathbf{x}), \ldots, g_M(\mathbf{x})]^T$ (instead of a scalar) and thus we want to maximize all elements of this vector *at the same time*. The "solution" turns out to be a set of vectors, see below, instead of a scalar as in conventional optimization. Eq. (1) is known as a *multi-objective optimization problem (MOOP)* or, alternatively, called a multi-criteria or vector optimization problem [Zad63, MA04, BDME08]. This type of problems arises in many engineering fields because of the difficulty to find a single scalar metric that describes exactly what we would like to achieve. However, the MOO methodology has received limited attention from the wireless communication community; our textbook [63] considers user fairness tradeoffs, [EESK08] looks into user scheduling aspects, and [NXS13] analyzes the balance between information and power transfer. The tradeoff between area throughput and energy efficiency has recently been studied in [CZXL11, NLM13] [64], among others, but only our work [64] has formulated it as a MOOP.

Since there is no total order of vectors, there is (generally) no global optimum to the MOOP in Eq. (1). This means that we cannot solve (1) in any globally optimal sense because there are *only subjectively optimal solutions*. This can be seen from the attainable objective set

$$\mathcal{G} = \{\mathbf{g}(\mathbf{x}) : \mathbf{x} \in \mathcal{X}\} \tag{2}$$

which contains all the combinations of objective values $\mathbf{g}(\mathbf{x}) = [g_1(\mathbf{x}), g_2(\mathbf{x}), \ldots, g_M(\mathbf{x})]^T$ that are simultaneously attainable under the available resources. The relationship between the resource bundle $\mathcal{X}$ and the attainable objective set $\mathcal{G}$ is visualized in Figure 1.

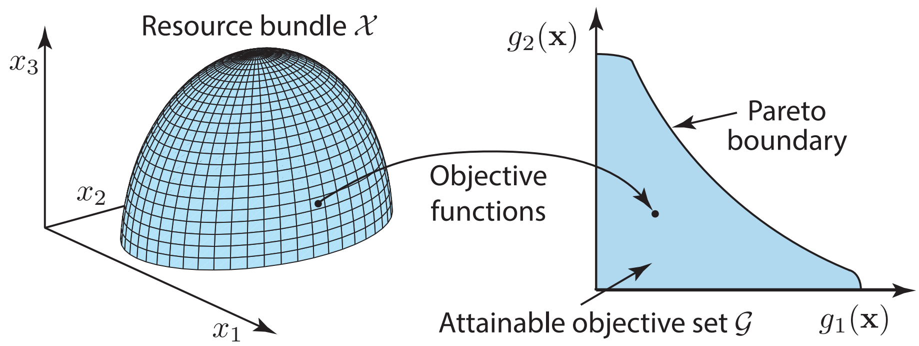


Figure 1: Illustration of a MOOP with a three-dimensional resource bundle $\mathcal{X}$ and a two-dimensional attainable objective set. For each resource utilization $\mathbf{x} = [x_1\ x_2\ x_3]^T \in \mathcal{X}$, the objective functions $g_1(\mathbf{x})$ and $g_2(\mathbf{x})$ assign a vector $\mathbf{g}(\mathbf{x}) \in \mathcal{G}$.

Any point in the interior of $\mathcal{G}$ can be discarded because there are other points in $\mathcal{G}$ that are more preferable (i.e., further from the origin) with respect to all the M objectives. The remaining points belong to the outer boundary, known as the *Pareto boundary*, and it is indicated in Figure 1. The Pareto boundary consists of the attainable operating points that cannot be objectively dismissed, because there is no other attainable operating point that is better with respect to all the M objectives. The Pareto boundary is (generally) an infinite set, but it is as close to global optimality that one can get when analyzing a MOOP. Hence, it is the Pareto boundary that a decision maker wants to learn and investigate when designing a wireless network that balance the M performance objectives in an efficient manner.

In short, the MOO methodology for optimizing wireless networks has the following steps:

1. Define resources: What are realistic communication resources and how can these be formalized as an analytically tractable resource bundle $\mathcal{X}$?

2. Define objectives: Which are the performance objectives and how can these be formulated mathematically, as $\mathbf{g}(\mathbf{x})$, in a realistic manner?

3. Feasibility test: How can one determine if a potential operating point is feasible or not? This often boils down to deriving and solving a new single-objective optimization problem.

4. Visualization: How can we utilize the feasibility test to visualize the Pareto boundary in a computationally efficient manner?

5. Decision support: How can we identify "good" operating points based on (partial) knowledge of the Pareto boundary? Is it possible to obtain necessary conditions for Pareto optimality or to define scalar metrics that combines the M objectives in a satisfying way?

Although the five steps in this methodology are well-established, it is very challenging to apply it to new open research problems. For example, a well-balanced modeling of resources and objectives is necessary to obtain feasibility tests with tractable computational complexity. Hence, any new application requires a large amount of mathematical modeling and analysis.

Project Description

The project is planned to begin in Jan. 2016 and span over four years. It consists of four research tasks that are partially overlapping in time, as described below. The joint theme of these tasks is network optimization where the infrastructure (e.g., deployment, interaction between access points, and hardware characteristics) are treated as optimization variables.

Theory and Methods: The planned research utilizes the mathematical methodology of multi-objective optimization [Zad63, MA04, BDME08], as outlined above. This method will be used to model and optimize wireless networks with respect to multiple conflicting performance objectives. The network consists of many spatially distributed access points that communicate wirelessly with user devices. Each access point and user device might be equipped with an array of antennas that allows for adaptive beamforming transmission using multiple-input multiple-output (MIMO) techniques. The network architecture will be modeled and optimized, for example, in terms of cell density and cell planning, hardware characteristics, and interaction between access points. The communication link between each access point and a user device is described by communication theoretic models, which describe the achievable data rates with practical coding and modulation. Key properties such as channel propagation characteristics, imperfect channel knowledge, and hardware imperfections will be taken into account [63]. Stochastic geometry methods will be used to describe network heterogeneity [BB09], such as non-uniform deployment, different classes of service requirements, and device capabilities.

As a general hypothesis, we believe that an attractive future network design is a dense deployments of "small" access points, each being equipped with MIMO technology for multiplexing of users and each being capable of collaborating in a user-centric fashion with neighboring access points to control the service quality of each user. The methodology of this project provides the means to verify the accuracy of this hypothesis, by deriving the optimal network design with respect to different performance objectives and expose the related tradeoffs.

Research Task 1: Beamforming optimization with realistic channel acquisition.

The initial research task in this project will revisit the conventional power control and beamforming optimization problems, which are usually formulated under the unrealistic assumption that the channel responses between all access points and user devices are perfectly known in the network. Realistic channel acquisition from training signaling and the impact of imperfect channel knowledge on the communication-theoretic data rates is essential in this task.

This task has two purposes. Firstly, the PhD student that is recruited for the project will have the opportunity to get familiar with the state-of-the-art methods, which are expected to be very useful starting point for the later tasks of this project. Finally, we expect to make original research contributions by analyzing a MOOP where the user throughput and energy efficiency are optimized with respect to the power and beamforming, under imperfect channel knowledge.

Research Task 2: Optimizing network density for heterogeneous user characteristics.

The users that are connected to wireless networks have heterogeneous characteristics, for example, in terms of geographical positions, mobility, rate demands, and processing capabilities (see "Purpose and Aims"). A well-designed network is deployed with this mind and adapts its transmissions to the user characteristics. The key to formulate this as a tractable design/optimization problem is to model the different user properties stochastically; the geographical distribution can be modeled as spatial point processes and random distributions can be assigned to describe the variability in other characteristics. The network can then be optimized analytically to maximize the average performance, with respect to several metrics.

In this task, the network is optimized with respect to the cell deployment (e.g., the density of access points), the transceiver characteristics (i.e., the number of antennas at access points and user devices), and the distribution of transmission power. The key originality lies in the fact that not only the transmit power allocation is optimized, but also the network infrastructure itself. Relevant performance metrics are the area data throughput (e.g., for different categories of users), the energy efficiency, the area power consumption, and the deployment cost. These metrics need to be mathematically rederived within the research task to take the variability in the novel set of optimization variables into account. Apart from deriving the fundamental tradeoffs and necessary optimality conditions, this research task can also provide insight on how to optimally serve high and low mobility users jointly in a network and how to handle user devices that request very different throughput levels.

Research Task 3: User-centric coordination and interaction between access points.

Traditionally, cellular wireless networks consist of a number of access points that cover non-overlapping geographical areas. This concept dates back to the 1970s and a key to success has been to avoid interference between the cells, for example, by dividing the time/frequency resources orthogonally between neighboring cells. Adaptive beamforming techniques, from multi-antenna arrays, can also be used to direct signals spatially towards the desired receivers and thereby mitigate inter-cell interference. Since modern networks are deployed much denser than in the past (e.g., 100 meter between access points instead of several kilometers), these methods for interference-avoidance are not be enough to provide decent user service.

If wireless networks are redesigned from a clean slate, the traditional cellular infrastructure might not be the desirable solution. The purpose of this research task is to optimize the interactions between the access points with respect to multiple performance objectives, including data throughput, energy efficiency, and deployment cost. Both network-centric and user-centric networks are considered; the former refers to networks where the access points form disjoint clusters to serve the users in their vicinity, while the latter refers to networks where each user is served by all of its surrounding access points. In the extreme case, where all access points collaborate, the network is essential “cell-free”.

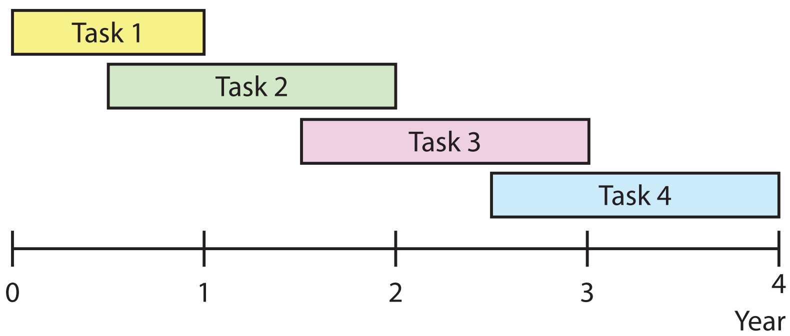
In addition to conventional design parameters, such as the distribution of transmit power between users, optimization variables in this research task are the size of the coordination clusters. The impact on the different objectives need to be modeled accurately.

Research Task 4: Optimizing transceiver hardware characteristics.

The predominate expressions for data throughput in communication networks have an underlying assumption of perfect hardware, which is a relatively good approximation when operating at low signal-to-interference-and-noise ratios (SINRs). In contrast, these throughput expressions can be very misleading in high SINR situations, which occur when the pathloss is small, coherent processing from multiple antennas are used, or when advanced interference mitigation processing is applied [5], [12]. The signal distortions due to quantization errors, I/Q imbalance, phase noise, non-linearities, and non-ideal filtering have a dominating impact on the throughput in high SINR situations.

The first step towards a realistic performance evaluation has been to revise the communication-theoretic models to take these hardware distortions into account. A new original step is taken in this research task, by treating the hardware quality as an optimization variable as well. Our recent work [1] shows that there is an inverse proportionality between the power consumption of transceiver circuits and the variance of the signal distortion. This key connection will be utilized to achieve tractable optimization problems in this research task. Typical performance metrics such as throughput and energy efficiency will be revisited from a MOO perspective, but with the hardware quality as a whole new dimension.

Time table: The research tasks are conducted in a sequential and partially overlapping manner:



The first task includes a review of the state-of-the-art, which is essential to all the tasks. Otherwise, the tasks are mutually independent, but modeling insight, algorithms, and optimization variables will be carried over between the tasks whenever possible.

Risk management: In order to operate the project according to the plan, the main challenge is to obtain realistic and still tractable mathematical problem formulations. We are convinced that this is possible, but in the unlikely event that a research task turns is more challenging than anticipated, parts of the analysis can be replaced by thorough numerical studies.

Project Implementation and Organisation: The project will be led by docent Emil Björnson and carried out at the Division of Communication Systems, Department of Electrical Engineering (ISY), Linköping University. The research tasks will be performed by the project leader (30% activity over 4 years) and by a new PhD student (80% activity over 4 years) that has not been recruited yet. Dr. Emil Björnson will be the main supervisor of this PhD student.

Significance

Many significant research contributions originate from the cross-pollination of theories from different research fields. This will be a pioneering project that combines the multi-objective optimization methodology with information/communication theory for wireless networks. While this combination was of limited interest when the networks were designed mainly for high peak data rates, the diverse performance objectives and heterogenous characteristics of the upcoming 5G networks call for a multi-objective design. Since the first 5G networks are expected in 2020, this project will be carried out alongside the development of 5G technology—thus making the project both very timely and practically relevant. The Division of Communication Systems at Linköping University has a track-record of pinpointing prominent emerging topics in wireless communications (e.g., massive MIMO) and making fundamental contributions to establish them as high-profile research areas. Network design by MOO methodology is a new topic that we believe in. Our initial works in [64] and [37] are very well received, and the latter received a Best Paper Award at the conference IEEE WCNC 2014.

The project tackles challenging network design problems that are particularly original in the sense of using the network infrastructure as optimization variables. The scientific results will be disseminated in peer-reviewed high impact international conferences and journals (e.g., one of each kind per research task). The pioneering nature of the project makes it ideal for tutorial presentations at international conferences. In addition to the scientific results, another major purpose and outcome of this project will be the education of a PhD student.

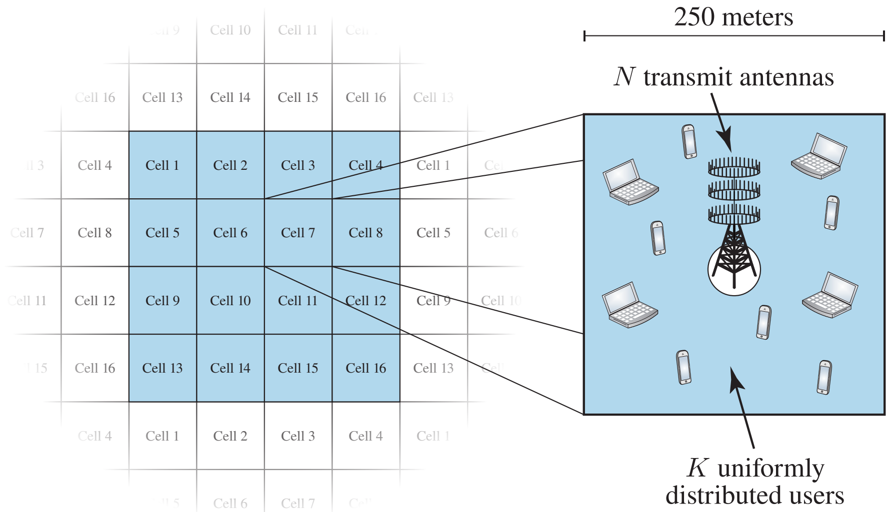


Figure 2: A wireless network with N transmit antennas per access point and K single-antenna user devices per cell. 16 cells are "wrapped around" to model a large area without any edges.

Preliminary Results

The feasibility and great potential of using multi-objective optimization methodology to analyze and design wireless networks were described in our recent survey paper [64]. Next, we provide an illustrative example from the survey paper. Suppose that we have a symmetric wireless network consisting of square cells of size 250×250 meters, where the cell area is $A = 0.25^2\,\text{km}^2$. Each cell consists of one access point that transmits to K users, which are uniformly distributed in the cell. The access point is equipped with an array of N antennas, which allows for multi-user transmission where each signal is directed spatially towards its intended user using adaptive zero-forcing beamforming [63]. The scenario is illustrated in Figure 2.

The resource variables in this example are the number of antennas N, the number of users K, and the total transmit power P per cell. The resource bundle is defined as

$$\mathcal{X} = \left\{ [K\ N\ P]^T : \begin{array}{c} 1 \leq K \leq \frac{N}{2}, \\ 2 \leq N \leq N_{\max}, \\ 0 \leq P \leq N P_{\max} \end{array} \right\} \tag{3}$$

where $N_{\max} = 500$ is the maximal number of antennas that can fit at the access point, $P_{\max} = 20\,\text{W}$ is the maximal emitted power per antenna, and the constraint $K \leq \frac{N}{2}$ can help reducing the interference in practice. A feasible resource utilization is denoted as $\mathbf{x} = [K\ N\ P]^T \in \mathcal{X}$.

We consider three of the objective functions described earlier:

$$\text{Average user rate:} \quad g_1(\mathbf{x}) = R_{\text{average}}(N, K, P) \quad [\text{bit/s/user}] \tag{4}$$

$$\text{Average area rate:} \quad g_2(\mathbf{x}) = \frac{K\, R_{\text{average}}(N, K, P)}{A} \quad [\text{bit/s/km}^2] \tag{5}$$

$$\text{Energy efficiency:} \quad g_3(\mathbf{x}) = \frac{K\, R_{\text{average}}(N, K, P)}{P_{\text{total}}(N, K, P)} \quad [\text{bit/J}]. \tag{6}$$

The data rate per user, $R_{\text{average}}(N, K, P)$, and the total power, $P_{\text{total}}(N, K, P)$, depend on the transmission schemes, hardware, and propagation environment. A main difficulty when using the MOO methodology is to find realistic and tractable models for functions like these.

Using (3) and (4)–(6), we have defined a MOOP of the generic type defined in Eq. (1). Using optimization methods, we can illustrate the tradeoffs between the three objectives. The tradeoff between the average user rate and energy efficiency is shown in Figure 3. The shape of the achievable objective set reveals that two objectives are aligned up to the point $g_1 = 20.4\,\mathrm{Mbit/s/user}$ and $g_3 = 11.1\,\mathrm{Mbit/J}$, where the maximal energy efficiency is achieved. The objectives are then conflicting, because the user rates can only be further increased by spending more power in a way that leads to drastic sacrifices in energy efficiency.

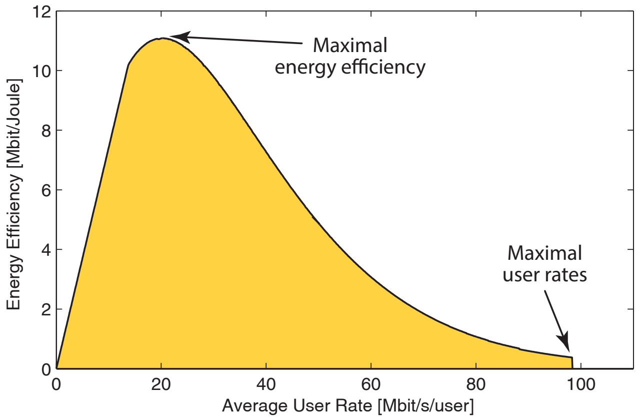


Figure 3: Visualization of the tradeoff between two objectives: the average rate per active user and the energy efficiency.

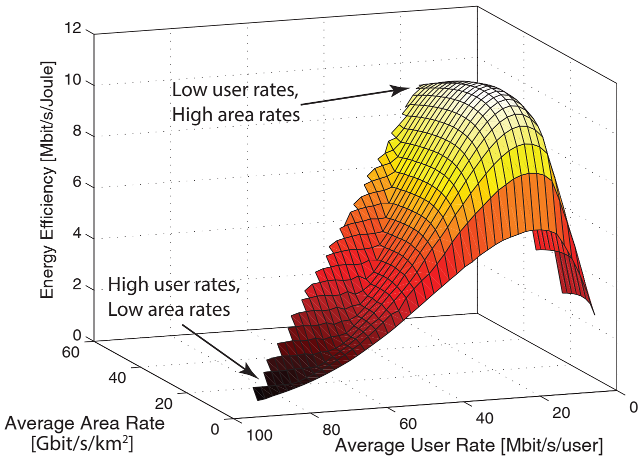


Figure 4: Visualization of the tradeoff between three objectives: the average user rate, the average area rate, and the energy efficiency.

The three-dimensional tradeoff between all three objectives is visualized in Figure 4. This figure reveals that high area rates are achieved when the data rates per user are small, and vice versa. Hence, high area rates are achieved by transmitting to many users simultaneously, while high rates per active user is only possible to a few simultaneous users. High energy efficiency can be achieved only when user load is high. The results proves that the network architecture needs to be flexible (e.g., in terms of switching between transmission schemes) if different operating points should be attainable in different traffic situations.

This example shows that the multi-objective optimization methodology can provide valuable insights on the interplay between different resources and performance objectives in cellular networks. Such behaviors and tradeoffs can also be predicted heuristically, but the multi-objective methodology is necessary to give rigorous and concrete proofs.

Independent line of research

The project leader worked with conventional network optimization in his PhD studies. During his postdoctoral studies, he identified the multi-objective optimization methodology while writing the textbook [63] together with the colleague Prof. Eduard Jorswieck (who have never been the advisor of the project leader). The main originality of this project lies in the idea of optimizing the network infrastructure jointly with the conventional design variables, which is an idea that the project leader got independently of others during his postdoctoral studies. He is among the first ones to consider these research problem, and the only one who is using the MOO methodology in this field. This project can thus sustain his position as an independent researcher in the forefront of this field. This proposal has been written independently by the project leader and is not related to any research projects by any of the former advisors of the project leader.

Form of employment

The project leader is employed as research fellow (swedish: biträdande universitetslektor), while the student will be employed as PhD student at Linköping University. Both will be employed with salary for the full duration of the project.

Additional Information

International and national collaboration

The project leader have already established collaboration on this and related topics with several internationally distinguished researchers; for example, Prof. Mérouane Debbah (professor, CentraleSupélec, France), Prof. Eduard Jorswieck (head of the Chair of Communications Theory, Dresden University of Technology, Germany), Ass. Prof. Luca Sanguinetti (University of Pisa, Italy), and Senior lecturer Michail Matthaiou (Queen's University Belfast, UK). The collaborations have resulted in the book [63] and the preliminary results such as [1], [2], [37] and [64]. We will maintain these collaborations within this project as well. The new PhD student will benefit from the large international contact network of the advisors and will naturally establish his/her own international network.

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See also the publication list in Appendix C.

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

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	Emil Björnson	30
2	Other personnel without doctoral degree	PhD student	80

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	2019	Total
1	Applicant	Emil Björnson	30	336,798	346,902	357,309	368,028	1,409,037
2	Other personnel without doctoral degree	PhD student	80	558,835	575,600	592,868	610,654	2,337,957
	Total			895,633	922,502	950,177	978,682	3,746,994

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	Publication	Publishing of papers	25,000	25,000	25,000	25,000	100,000
2	Travels	Conference travels	64,620	66,559	68,555	70,612	270,346
	Total		89,620	91,559	93,555	95,612	370,346

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	895,633	922,502	950,177	978,682	3,746,994		3,746,994
Running costs	89,620	91,559	93,555	95,612	370,346		370,346
Depreciation costs					0		0
Premises					0		0
Subtotal	985,253	1,014,061	1,043,732	1,074,294	4,117,340	0	4,117,340
Indirect costs					0		0
Total project cost	985,253	1,014,061	1,043,732	1,074,294	4,117,340	0	4,117,340

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

This project has three cost categories: salaries, travels, and publication. The cost categories are now described in detail.

Salaries: We plan to hire a new PhD student who will be fully involved in the project. This corresponds to an activity level of 80% of full time over four years (the remaining 20% are teaching-related and are not covered by the project). In addition, the project leader Dr. Emil Björnson will be involved in the project at 30% of full time. The salary computation below includes 35% overhead (OH) costs from Linköping University and 56% payroll taxes/expenses ("lönekonstnadpåslag" (LKP)). A 3% annual salary growth rate is also included.

Travels: The travel costs are assumed to be 15% of the salary costs (before the overhead costs have been applied). This amount covers the costs (registration, travels, accommodation, and daily allowance) for research dissemination at 1-2 international conferences per year for the PhD student and 1 conference per year for the project leader.

Publication: The publication in high-impact journals is expected to cost 25 kSEK per year.

Other funding

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

Other funding for this project

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

CV and publications

CV

Appendix B: Curriculum Vitae – Emil Björnson (830918-3930)

1. Higher Education Qualification

Master of Science (Engineering Mathematics, 2007), Lund University, Lund, Sweden.

2. Doctoral Degree (2011, Telecommunications)

Thesis title: *Multiantenna Cellular Communications: Channel Estimation, Feedback, and Resource Allocation*.
Supervisors: Björn Ottersten and Mats Bengtsson, KTH Royal Institute of Technology, Stockholm, Sweden.

3. Postdoctoral Positions

Joint Postdoctoral Researcher (100% research) at Supélec, Gif-sur-Yvette, France, and KTH Royal Institute of Technology, Stockholm, Sweden. This position was sponsored by an International postdoc grant from Vetenskapsrådet (VR). 75% of the time was spent at Supélec. July 2012 – Dec. 2013 (full time), Jan. 2014 - July 2014 (80% of full time).

Postdoc in Telecommunications (100% research), Department of Signal Processing, KTH Royal Institute of Technology, Stockholm, Sweden. Dec. 2011 – June 2012.

4. Qualification Required for Appointment as a Docent

Appointed as docent by Linköping University, Feb. 2015.

5. Current Position

Assistant Professor (biträdande universitetslektor), Division of Communication Systems, Department of Electrical Engineering, Linköping University, Linköping, Sweden, (Percentage of research is not specified). Jan 2014 - July 2014 (20% of full time), Aug 2014 – Dec 2017 (full time).

This position is part of the tenure-track program, which leads to the promotion to a permanent associate professor position following a successful application within four years.

6. Previous Positions

- Teaching Assistant, Department of Signal Processing, KTH Royal Institute of Technology, Stockholm, Sweden. *(Part-time teaching in the undergraduate/graduate level courses and supervision of two Master Degree Projects.)* April 2007 – December 2010.
- Developer in Computer Vision, Axis Communications AB, Lund, Sweden, June 2006 – August 2006.
- Teaching Assistant, Department of Electrical and Information Technology, Lund University, Lund, Sweden. *(Part-time teaching/development of the course Signals and Communications.)* March 2006 – June 2006.
- Teaching Assistant, Mathematics (Faculty of Engineering), Lund University, Lund, Sweden. *(Part-time teaching in undergraduate mathematics.)* September 2003 – March 2006.
- Freelancing Project Leader and Creative Writer, Neogames AB, Gothenburg, Sweden, *(Part-time developer of two Swedish commercial role playing games.)*
April 2000 – September 2005, October 2007 – April 2009.

8. Supervision

Main supervisor of the PhD students Trinh Van Chien (2015-) and Daniel Morano Verenzuela (2015-) at Linköping University, Linköping, Sweden.

Co-supervisor of Antonios Pitarokoilis (2014-), Marcus Karlsson (2015-), and Hei Victor Cheng (2015-) at Linköping University, Linköping, Sweden.

9. Other merits of relevance to the application

Research Grants

2015 Grant for the project "Radio Resource Management in Massive MIMO Communication Systems", Center for Industrial and Information Technology (CENIIT).

2012-2014 International Postdoc Grant for the project "Optimization of Green Small-Cell Telecommunication Networks", Swedish Research Council (Vetenskapsrådet).

Awards & Honors

2015 **2014 Outstanding Young Researcher Award**, from IEEE ComSoc Europe Middle East and Africa (EMEA) Region.

2014 **Best Paper Award**, IEEE Sensor Array and Multichannel Signal Processing Workshop (SAM)" for the paper "Efficient Linear Precoding for Massive MIMO Systems using Truncated Polynomial Expansion", co-authored by A. Müller, A. Kammoun, and M. Debbah.

2014 **Best Paper Award**, IEEE Wireless Communications and Networking Conference (WCNC) for the paper "Designing Multi-User MIMO for Energy Efficiency: When is Massive MIMO the Answer?", co-authored by L. Sanguinetti, J. Hoydis, and M. Debbah.

2012, 2013, 2014 **Exemplary Reviewer** in IEEE Communications Letters, selected both 2012 and 2013.

2011 **Best Student Paper Award**, IEEE International Workshop on Computational Advances in Multi-Sensor Adaptive Processing (CAMSAP) for the paper "Computational Framework for Optimal Robust Beamforming in Coordinated Multicell Systems", co-authored by M. Bengtsson, G. Zheng, and B. Ottersten.

2009 **Best Paper Award**, International Conference on Wireless Communications and Signal Processing (WCSP) for the paper "On the Principles of Multicell Precoding with Centralized and Distributed Cooperation", co-authored by B. Ottersten.

Professional Activities

- *Keynote Speaker:* IEEE International Workshop on Computer-Aided Modeling Analysis and Design of Communication Links and Networks (CAMAD), Athens, Dec. 2014.
- *Co-Chair of the Massive MIMO Communications Symposium* at IEEE Global Conference on Signal and Information Processing (GlobalSIP), Atlanta, USA, Dec. 2014.
- *Keynote Speaker:* Wireless Evolution Beyond 2020 Workshop, Istanbul, Apr. 2014.
- *Tutorial Lecturer:* IEEE ICC 2015, IEEE VTC-Spring 2015, 5GrEEn Summer School 2014, IEEE ICC 2014, Newcom# Spring School 2014, and IEEE PIMRC 2013.
- *Keynote Speaker* at the workshop "Signal Processing and Optimization for Wireless Communications: In Memory of Are Hjorungnes," Trondheim, Norway, May 2013.
- *European Research Projects:* Task leader in the MAMMOET (FP7) project and active participant in the projects AMIMOS (FP7), COOPCOM (FP6), and WINNER+ (Celtic).
- *Frequent Reviewer* in IEEE Trans. on Signal Process., IEEE Trans. on Wireless Commun., IEEE Trans. on Commun., IEEE Commun. Letters, and several IEEE conferences.

Publication list

Appendix C: Emil Björnson — Publications

Publication Output in Brief

- 1 scientific textbook (monograph)
- 19 journal and 2 magazine articles
- 43 conference papers
- 991 citations in total, whereof one article has received 172 citations
- h-index of 16
- Co-authorship with more than 50 researchers

The five publications that are most important to this project are marked with an asterisk (*).

The number of citations are given for all articles with 5 or more citations. The citation statistics were extracted from Google Scholar (https://scholar.google.se/citations?user=Maij4akAAAAJ) on March 31, 2015.

1. Peer-reviewed original articles

[1] Emil Björnson, Michail Matthaiou, Mérouane Debbah, "Massive MIMO with Arbitrary Non-Ideal Arrays: Hardware Scaling Laws and Circuit-Aware Design," *IEEE Transactions on Wireless Communications*, To appear.

[2] * Emil Björnson, Luca Sanguinetti, Jakob Hoydis, Mérouane Debbah, "Optimal Design of Energy-Efficient Multi-User MIMO Systems: Is Massive MIMO the Answer?," *IEEE Transactions on Wireless Communications*, To appear. **Number of citations: 17**

[3] Mikko Vehkaperä, Taneli Riihonen, Maksym Girnyk, Emil Björnson, Mérouane Debbah, Lars K. Rasmussen, Risto Wichman, "Asymptotic Analysis of MIMO Channels With Transmitter Noise and Mismatched Decoding," *IEEE Transactions on Communications*, vol. 63, no. 3, pp. 749-765, March 2015.

[4] Luca Sanguinetti, Aris L. Moustakas, Emil Björnson, Mérouane Debbah, "Large System Analysis of the Energy Consumption Distribution in Multi-User MIMO Systems with Mobility," *IEEE Transactions on Wireless Communications*, vol. 14, no. 3, pp. 1730-1745, March 2015.

[5] * Emil Björnson, Jakob Hoydis, Marios Kountouris, Mérouane Debbah, "Massive MIMO Systems with Non-Ideal Hardware: Energy Efficiency, Estimation, and Capacity Limits," *IEEE Transactions on Information Theory*, vol. 60, no. 11, pp. 7112-7139, November 2014. **Number of citations: 54**

[6] Abla Kammoun, Axel Müller, Emil Björnson, Mérouane Debbah, "Linear Precoding Based on Truncated Polynomial Expansion: Large-Scale Multi-Cell Systems," *IEEE Journal of Selected Topics in Signal Processing*, vol. 8, no. 5, pp. 861-875, October 2014. **Number of citations: 14**

[7] Nafiseh Shariati, Emil Björnson, Mats Bengtsson, Mérouane Debbah, "Low-Complexity Polynomial Channel Estimation in Large-Scale MIMO with Arbitrary Statistics," *IEEE Journal of Selected Topics in Signal Processing*, vol. 8, no. 5, pp. 815-830, October 2014. **Number of citations: 6**

[8] Emil Björnson, Michail Matthaiou, Mérouane Debbah, "A New Look at Dual-Hop Relaying: Performance Limits with Hardware Impairments," *IEEE Transactions on Communications*, vol. 61, no. 11, pp. 4512-4525, November 2013. **Number of citations: 9**

[9] Dimitrios Katselis, Cristian Rojas, Mats Bengtsson, Emil Björnson, Xavier Bombois, Nafiseh Shariati, Magnus Jansson, Håkan Hjalmarsson, "Training sequence design for MIMO channels: an application-oriented approach," EURASIP Journal on Wireless Communications and Networking, 2013:245, 2013. **Number of citations: 8**

[10] Emil Björnson, Marios Kountouris, Mats Bengtsson, Björn Ottersten, "Receive Combining vs. Multi-Stream Multiplexing in Downlink Systems with Multi-Antenna Users," *IEEE Transactions on Signal Processing*, vol. 61, no. 13, pp. 3431-3446, July 2013. **Number of citations: 7**

[11] Michail Matthaiou, Agisilaos Papadogiannis, Emil Björnson, and Mérouane Debbah, "Two-way Relaying under the Presence of Relay Transceiver Hardware Impairments," *IEEE Communications Letters*, vol. 17, no. 6, pp. 1136-1139, June 2013. **Number of citations: 7**

[12] Emil Björnson, Per Zetterberg, Mats Bengtsson, Björn Ottersten, "Capacity Limits and Multiplexing Gains of MIMO Channels with Transceiver Impairments," *IEEE Communications Letters*, vol. 17, no. 1, pp. 91-94, January 2013. **Number of citations: 39**

[13] Emil Björnson, Mats Bengtsson, Björn Ottersten, "Pareto Characterization of the Multicell MIMO Performance Region With Simple Receivers," *IEEE Transactions on Signal Processing*, vol. 60, no. 8, pp. 4464-4469, August 2012. **Number of citations: 25**

[14] * Emil Björnson, Gan Zheng, Mats Bengtsson, Björn Ottersten, "Robust Monotonic Optimization Framework for Multicell MISO Systems," *IEEE Transactions on Signal Processing*, vol. 60, no. 5, pp. 2508-2523, May 2012. **Runner-Up for IEEE Sweden VT-COM-IT Joint Chapter Best Student Journal Paper Award. Number of citations: 56**

[15] Emil Björnson, Niklas Jaldén, Mats Bengtsson, Björn Ottersten, "Optimality Properties, Distributed Strategies, and Measurement-Based Evaluation of Coordinated Multicell OFDMA Transmission," *IEEE Transactions on Signal Processing*, vol. 59, no. 12, pp. 6086-6101, December 2011. **Number of citations: 47**

[16] Emil Björnson, Eduard Jorswieck, Björn Ottersten, "Impact of Spatial Correlation and Precoding Design in OSTBC MIMO Systems," *IEEE Transactions on Wireless Communications*, vol. 9, no. 11, pp. 3578-3589, November 2010. **Number of citations: 16**

[17] Emil Björnson, Randa Zakhour, David Gesbert, Björn Ottersten, "Cooperative Multicell Precoding: Rate Region Characterization and Distributed Strategies with Instantaneous and Statistical CSI," *IEEE Transactions on Signal Processing*, vol. 58, no. 8, pp. 4298-4310, August 2010. **Number of citations: 172**

[18] Emil Björnson, Björn Ottersten, "A Framework for Training-Based Estimation in Arbitrarily Correlated Rician MIMO Channels with Rician Disturbance," *IEEE Transactions on Signal Processing*, vol. 58, no. 3, pp. 1807-1820, March 2010. **Number of citations: 85**

[19] Emil Björnson, David Hammarwall, Björn Ottersten, "Exploiting Quantized Channel Norm Feedback through Conditional Statistics in Arbitrarily Correlated MIMO Systems," *IEEE Transactions on Signal Processing*, vol. 57, no. 10, pp. 4027-4041, October 2009. **Number of citations: 43**

2. Peer-reviewed conference contributions

[20] Emil Björnson, Luca Sanguinetti, Marios Kountouris, "Designing Wireless Broadband Access for Energy Efficiency: Are Small Cells the Only Answer?," *Proceedings of IEEE International Conference on Communications (ICC)*, June 2015.

[21] Serveh Shalmashi, Emil Björnson, Marios Kountouris, Ki Won Sung, Mérouane Debbah, "Energy Efficiency and Sum Rate when Massive MIMO meets Device-to-Device Communication," *Proceedings of IEEE International Conference on Communications (ICC)*, June 2015.

[22] Antonios Pitarokoilis, Emil Björnson, Erik G. Larsson, "Optimal Detection in Training Assisted SIMO Systems with Phase Noise Impairments," *Proceedings of IEEE International Conference on Communications (ICC)*, June 2015.

[23] Hei Victor Cheng, Daniel Persson, Emil Björnson, Erik G. Larsson, "Massive MIMO at Night: On the Operation of Massive MIMO in Low Traffic Scenarios," *Proceedings of IEEE International Conference on Communications (ICC)*, June 2015.

[24] Jingya Li, Emil Björnson, Tommy Svensson, Thomas Eriksson, Mérouane Debbah, "Optimal Design of Energy-Efficient HetNets: Joint Precoding and Load Balancing," *Proceedings of IEEE International Conference on Communications (ICC)*, June 2015.

[25] Mikko Vehkaperä, Taneli Riihonen, Maksym Girnyk, Emil Björnson, Mérouane Debbah, Lars Rasmussen, Risto Wichman, "Asymptotic Analysis of Asymmetric MIMO Links: EVM Limits for Joint Decoding of PSK and QAM," *Proceedings of IEEE International Conference on Communications (ICC)*, June 2015.

[26] Luca Sanguinetti, Emil Björnson, Mérouane Debbah, Aris Moustakas, "Optimal Linear Precoding in Multi-User MIMO Systems: A Large System Analysis," *Proceedings of IEEE Global Communications Conference (GLOBECOM)*, December 2014.

[27] Emil Björnson, Erik G. Larsson, Mérouane Debbah, "Optimizing Multi-Cell Massive MIMO for Spectral Efficiency: How Many Users Should Be Scheduled?," *Proceedings of IEEE Global Conference on Signal and Information Processing (GlobalSIP)*, December 2014.

[28] Abla Kammoun, Axel Müller, Emil Björnson, Mérouane Debbah, "Low-Complexity Linear Precoding for Multi-Cell Massive MIMO Systems," *Proceedings of European Signal Processing Conference (EUSIPCO)*, September 2014.

[29] Xinlin Zhang, Michail Matthaiou, Mikael Coldrey, Emil Björnson, "Energy Efficiency Optimization in Hardware-Constrained Large-Scale MIMO Systems," *Proceedings of International Symposium on Wireless Communication Systems (ISWCS)*, August 2014.

[30] Axel Müller, Abla Kammoun, Emil Björnson, Mérouane Debbah, "Efficient Linear Precoding for Mas- sive MIMO Systems using Truncated Polynomial Expansion," *Proceedings of IEEE Sensor Array and Multi-channel Signal Processing Workshop (SAM)*, June 2014. **Best Student Paper Award.**

[31] Xinlin Zhang, Michail Matthaiou, Emil Björnson, Mikael Coldrey, Mérouane Debbah, "On the MIMO Capacity with Residual Transceiver Hardware Impairments," *Proceedings of IEEE International Conference on Communications (ICC)*, June 2014. **Number of citations: 5**

[32] Xinlin Zhang, Michail Matthaiou, Mikael Coldrey, Emil Björnson, "Impact of Residual Transmit RF Impairments on Training-Based MIMO Systems," *Proceedings of IEEE International Conference on Communications (ICC)*, June 2014.

[33] Emil Björnson, Michail Matthaiou, Mérouane Debbah, "Circuit-Aware Design of Energy-Efficient Massive MIMO Systems," *Proceedings of International Symposium on Communications, Control, and Signal Processing (ISCCSP)*, May 2014. **Number of citations: 6**

[34] Emil Björnson, Michail Matthaiou, Mérouane Debbah, "Massive MIMO Systems with Hardware-Constrained Base Stations," *Proceedings of IEEE Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, May 2014.

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3. Monographs

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4. Research review articles

[64] * Emil Björnson, Eduard Jorswieck, Mérouane Debbah, Björn Ottersten, “Multi-Objective Signal Processing Optimization: The Way to Balance Conflicting Metrics in 5G Systems,” *IEEE Signal Processing Magazine* (Special Issue on Signal Processing for the 5G Revolution), vol. 31, no. 6, pp. 14-23, November 2014.

[65] Emil Björnson, Mats Bengtsson, Björn Ottersten, "Optimal Multi-User Transmit Beamforming: Difficult Problem with a Simple Solution Structure," *IEEE Signal Processing Magazine*, vol. 31, no. 4, pp. 142-148, July 2014. **Number of citations: 10**

6. Patents

Erik G. Larsson, Emil Björnson, "Pilot collision resolution in massive MIMO", filed at February 23, 2015.

7. Open-Access Computer Software

- To enable reproducibility of research results, I have published several Matlab code packages online. These reproduce all the simulation results in 8 journal articles and 2 conference papers, and also some of the results in my textbook [63].
  Link: `https://github.com/emilbjornson`

8. Popular Science Articles

- The introduction chapter of my doctoral thesis *"Multiantenna Cellular Communications: Channel Estimation, Feedback, and Resource Allocation"* was written as popular science. A Swedish translation is published online:
  `http://www.commsys.isy.liu.se/~ebjornson/introduktion_emil_bjornson.pdf`
- Major contributions to several English encyclopedia articles on Wikipedia: *"Channel State Information", "Precoding", and "Spatial Correlation"*.

CV

Name: Emil Björnson	**Doctorial degree:** 2011-12-15
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Research education

Dissertation title (swe)

Dissertation title (en)

Multiantenna Cellular Communications: Channel Estimation, Feedback, and Resource Allocation

Organisation	Unit	Supervisor
Kungliga Tekniska Högskolan, Sweden Sweden - Higher education Institutes	Avdelningen för Signalbehandling	Björn Ottersten

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
20204. Telekommunikation	978-91-7501-114-1	2011-12-15

Publications

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Björnson, Emil 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.