Application

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2015-04081	Pappas, Nikolaos	NT-14

Information about applicant

Name: Nikolaos Pappas

Doctorial degree: 2012-08-24

Birthdate: 19820918

Academic title: Doktor

Gender: Male

Employer: Linköpings universitet

Administrating organisation: Linköpings universitet

Project site: Institutionen för teknik och naturvetenskap (ITN)

Information about application

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Project title (english): Methodologies for Discovering the Ultimate Limits of the Wireless Networks and Mechanisms to Achieve them

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Descriptive data

Project info

Project title (Swedish)*

Metoder för att upptäcka den yttersta prestandagränsen för trådlösa nätverk samt mekanismer för att uppnå dem

Project title (English)*

Methodologies for Discovering the Ultimate Limits of the Wireless Networks and Mechanisms to Achieve them

Abstract (English)*

In this proposal we will focus on discovering ultimate performance limits of wireless networks. Our study will initially target on the stable throughput region of multiple access networks, which is the network-level equivalent notion of the Shannon channel capacity, for sources with random packet arrivals. A key area to investigate is the effect of timing channels and finite blocklength codes on stable throughput. Another key performance area that we will focus on is that of delay. With the existing tools the analysis of delay in wireless networks seems intractable. To overcome this barrier of analytical characterization we propose to utilize new metrics such as the Age of Information. Finally, we will leverage long standing techniques, such as information caching, in the wireless networks aiming to approach the limits by exploiting methods taking into account the data traffic statistical properties and predict the user demand.

Popular scientific description (Swedish)*

Trådlösa nätverk och dess användning har blivit närvarade i allt många delar av vardagslivet. Den ökande efterfrågan på nätverkstjänster driver den tekniska utvecklingen i området, och skapar ett behov att utveckla en teoretisk bas för att vägleda design av system och nätverk utifrån vad teoretiskt är ytterst möjligt. Därmed kan nya teknik tas fram och skapa potential för ett paradigmskifte för hur at nätverk ska byggas.

Informationsteori och kommunikationssystem har varit två viktiga vetenskapliga discipliner för att studera de grundläggande lagarna som styr informationsöverföring i nätverk. Redan under tidiga dagar av kommunikationsnätverk hade det funnit indikationer på att dessa discipliner kommer att konvergera på grund av likartade koncept och metodik. Dock kvarstår idag ett stort gap mellan de två disciplinerna. Först och främst kommer projektet att undersöka kapacitetsgränser av kommunikationsnätverk genom att sammanfoga teorier inom informationsteori och kommunikationssystem.

Forsknings ska även ta hänsyn till den stora betydelsen att minimera fördröjningen för meddelandeutbyte in tidskritiska tillämpningar, t ex inom samhällsberedskap. Den nuvarande komplexiteten i kommunikationsnätverk, bland annat i trådlösa nät, gör att analysen av tidsfördröjning är extremt svårt om inte omöjligt. Den andra inriktningen i projektet är att utveckla nya sätt att tackla utmaningen, genom att introducera ett prestandamått som motsvara hur färsk information är.

Den tredje delen i projektet handlar om mellanlagring av data, som har potential att lyfta kapacitetsgränsen ytterligare. Mellanlagring utnyttjar egenskaper hos datatrafiken genom att prediktera användarnas efterfråga. Detta leder till ett mer effektivt system för att distribuera data med trådlösa nätverk, och skapar nya möjligheter såväl användare, operatörer, samt systemtillverkare.

Forskningen längs ovanstående tre föreslagna inriktningarna levererar resultat som båda leder till framsteg i grundforskningen av kommunikationssystem, och genererar nytta till slutanvändare av trådlösa kommunikationstjänster.

Project period

Number of project years*

4

Calculated project time*

2016-01-01 - 2019-12-31

Deductible time

Deductible time

Cause	Months
Career age: 31	

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 > 20204. Telekommunikation

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

Keyword 1*

wireless networking

Keyword 2*

stable throughput

Keyword 3*

delay

Keyword 4

caching

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*

Not Applicable.

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

Methodologies for Discovering the Ultimate Limits of the Wireless Networks and Mechanisms to Achieve them

1 Purpose and aims

The field of telecommunications stands currently at the forefront of a new era which is characterized by the transition to the new generation of wireless communications, namely the rise of 5G. With the recent explosion of the Machine-to-Machine (M2M) communications and the Internet-of-Things applications, the internet traffic is growing exponentially. Future networks should support applications with extremely variant Quality of Service (QoS) requirements, from low throughput and generally medium delay (M2M) to very high throughput and low delay (high definition real-time video), thus the characterization of the performance limits is very important.

Information theory is the tool to find the ultimate limits of communication networks in terms of data rates. *Since the early days of Information Theory it was realized that a major limitation of its use in Communication Systems is the inability to handle bursty traffic and queuing delay*. The information theoretic capacity region is derived under the assumption of saturated queues. In communication networks bursty data and delay are central and indispensable concepts.

The maximum stable throughput region is the equivalent metric for the information theoretic capacity region and is obtained for sources with random arrivals. The major difficulty in obtaining the maximum stable throughput region is the interacting queues; in a network (not only a wireless one) when a queue empties ceases to complete for communication resources with the other queues. A fundamental counter intuitive observation is:

When traffic is bursty, the capacity region of a multi-user system generally increases. Thus, the traditional view i.e. when all users remain backlogged, leads to lower data rates![1]

The relation between the information theoretic capacity region and the maximum stable throughput region is yet to be characterized in general. However, there are some papers that study this relationship for some small networks. **In this project we will work on this direction, trying to bridge the gap between traditional Information Theory and Communication Networks**.

Except data rates, the study of delay is of significant importance as another performance metric. Despite the progress in the study of wireless networks, the characterization of delay remains a burden except a few small networks. The major difficulty for characterizing the delay remains the interactions of users and the complexity of communication networks. Recently a new metric/concept was proposed in order to capture the need for real-time status updates, the *Age of Information*[2]. This metric can play a pivotal role since it could help to overcome the roadblock of delay computation and can capture the *freshness of information* inside a network. The *Timely Throughput* which was introduced recently, goes a step further and measures the average number of "successful deliveries" i.e., the packets delivered before the deadline, as *an analytical metric for evaluating both throughput and QoS for delay-constrained flows*. The aforementioned new metrics are discussed in Section 3, play a major role in characterizing the ultimate limits of future wireless networks.

The rapid increase of wireless data traffic has significant implication for the wireless networks. At the same time the maturity of current systems (LTE-Advanced and IEEE 802.11ac) does not allow dramatic improvements in spectral efficiency. Thus, a disruptive, radically innovative approach to the solution of this problem is required.

[1] More details can be found in [1, 2].

[2] In a wireless communication system where a source node transmits status updates to a destination node the status update is a message, containing information about one or more variables of interest, and the time of generation of the sample. Typically, it takes a random time until the packet is successfully delivered through the network. If the most recently received update carries the time stamp $u(t)$, which characterizes the instant of generation of the update, then the age, is defined as the random process $\Delta(t) = t - u(t)$. Hence, the Age is the time elapsed since the last received sample was generated [3, 4].

One of the factors that affect the performance of wireless networks is the available bandwidth. Furthermore, the data traffic has some interesting properties: (i) the user activity is highly asynchronous and (ii) there is high content reuse, in the sense that the demands are concentrated on a small set of popular files. Exploiting the aforementioned properties new methodologies can be developed in order to provide bandwidth spatial reuse gains. Wireless networks are becoming denser, storage capacity is growing rapidly and is one of the cheapest network resources which is available in infrastructure nodes and in user devices. Thus, the asynchronous content reuse can be turned into bandwidth spatial reuse. Furthermore, the Quality of Experience of the user will be improved by reducing the delay and also the interference inside the network. By deployment of caching at the edge of wireless networks we target to:

Use caching to transform memory into bandwidth!

More specifically, our goal is to investigate the caching capabilities at the nodes of wireless networks.

The research objectives of this proposal can be divided into two categories:

- Characterizing the ultimate limits of the wireless networks;
- Approaching the limits of wireless networks by exploiting the characteristics of data traffic by predicting and anticipating user demand.

The strength of the proposed research lies in:

- The immense interest of the research community in characterizing the performance of wireless networks and finding new techniques to advance their limits, that also find a wide variety of industrial applications;
- The strong background of the applicant (Dr. Nikolaos Pappas) in the fields of cooperative networks, queuing theory and stochastic geometry that are necessary to achieve the goals of the proposed project;
- The strong Swedish and international support of world-leading experts in the field along with the local complementary expertise of the Linköping University collaborators.

The project will involve fundamental research for Communication Network Theory and also will propose new methodologies for pushing the limits of wireless networks by leveraging the properties of data traffic.

2 Survey of the field

The field of wireless networking has been the object of increasing attention since the early seventies [2]. The vast majority of the early works focused on the simple Multiple Access model [5] with emphasis on random access and collision channels. It was determined at that time that the measure of throughput region, as an alternative to the capacity region (which is the focus of Information Theory) had to be adjusted to include the case of bursty arrivals. Thus the notion of Stable Throughput Region was born [6, 2, 7, 8]. Since then, the issue of combining Information Theory and Networking emerged to the forefront [2, 9]. Thus, an important question is the relation between capacity region, throughput region, and stable throughput region. This addresses both the issue of integration of the two fields as well as the issue of bursty traffic [8]. Furthermore they include the coupling of delay and capacity [10], the approximation of capacity regions [11], the duality between multiple access and broadcasting [12], and the incorporation of multi-user detection and multi-packet reception capability in ad hoc network models [10]. The stable throughput region has been investigated so far in simple topologies [10, 7, 13, 14, 15], additionally the effect of energy harvesting is considered [16, 17, 18].

The Principal Investigator of the proposal has contributed substantially in several of these aspects of the field, as outlined in the Preliminary Results Section.

In many applications, the timeliness with which a system presents its current status to a receiver is of critical importance [3, 4]. Take for instance news and weather reports, updates on social networks and vehicular status in intelligent transportation systems. To quantify this, the concept of *Age of Information* has been introduced, capturing the elapsed time from the most recently generated status update received. A line of works have presented the first analyses on the notion of age of information [3, 4, 19, 20]. Average age has been investigated in [21]. The case of multiple sources were first investigated in [22]. **The main result is that optimizing the timeliness of updates through the age of information metric is not equivalent to neither optimizing for throughput, nor for minimizing delay**. For instance, throughput can be maximized by making the source send updates as fast as possible. This may lead to the monitor receiving the information delayed because the sent messages get backlogged in the communication system. Although the delay of status updates could be decreased by reducing the rate of updates, this may also lead to the receiver having unnecessarily outdated status information because of a sparse updates. Randomness in network delays can cause packets to arrive out of order and render the information they carry obsolete. The average age of information under this consideration was studied in [23]. In [24, 25], a simple queue management technique was proposed for reducing the average age of information and the number of obsolete packets.

Among the many applications that benefit from wireless networks, those with quality of service (QoS) constraints are increasingly of interest. The packets for such applications have strict-per-packet deadline; and if a packet is not delivered successfully by its deadline, it will not be useful anymore. So, one of the most important questions for such networks is how much is the ultimate capacity for delay-sensitive traffic? In [26, 27, 28] the notion of timely throughput was proposed which measures the long-term average number of successful deliveries (i.e., the packets delivered before a deadline) for each user as an analytical metric for evaluating both throughput and QoS for delay-constrained flows.

With the recent ubiquity of high end multimedia capable mobile devices the demand for such high QoS services has dramatically risen. This is putting wireless networks under an enormous strain of packet delivery deadlines. A way to achieve throughput scalability is to enable smart caching not only on the access network but also on the wireless devices.

The state-of-art caching network capacity problem can be summarized as: Given a certain network topology and user demand profile assumed to be known, design a cache placement scheme and a delivery scheme such that the per-user throughput is maximized. In that formulation the caching essentially operates in two phases: (i) a placement phase, where consists of setting up the caches in the network under their memory constraints and (ii) a delivery phase, that consists of transmitting codewords such that each user, based on the received signal and the content of his or her own cache, is able to successfully decode the requested file.

Among the various network architectures and coding schemes, the following ones have received more attention:

- Femtocaching [29]: This work considers caching at infrastructure helper nodes (i.e. small-cell base stations) and the network is modeled as a bipartite graph where user nodes are connected to helper nodes through non-interfering links of fixed average capacity.
- Caching in the user nodes with device-to-device (D2D) communications [30]: In this work, there are no infrastructure nodes and the users nodes are both helpers and demand destinations so that contents are exchanged through D2D communications.
- Coded multicasting [31]: In this case, the network topology consists of just one sender (e.g. a base station) and several user nodes, each equipped with a cache of finite memory. There is no D2D communication between users.

Within the previously described setup the main result is that, the per-user throughput grows linearly in the size of the cache memory and inversely in the number of files. This is truly remarkable since it shows that caching at the edge allows to design wireless networks such that a fixed per-user throughout can be guaranteed irrespectively of how large the number of users is in the network. **This is in contrast to current cellular networks in which at some point the cell capacity is saturated and no more users can join the system without causing throughput degradation to the others**.

Despite this groundbreaking nature, the notion of wireless caching is in its infancy and remains yet still untested in realistic networks. This is because the current state-of-the-art in wireless caching relies on the following limiting assumptions:

- The network topology is fixed and does not capture the wireless channel characteristics [29, 30, 31];
- The popularity distribution remains fixed and is assumed to be known [29, 30, 31].

All this makes the potential applicability of caching in realistic wireless networks still unclear and open. Caching is expected that will radically change the way wireless networks operate and can constitute a paradigm shift. By leveraging the characteristics of data traffic and anticipating user demand caching will be closer for approaching the performance limits of wireless networks.

3 Project description

In this proposal we outline a research approach to develop a theoretical base to track the ultimate limits of wireless networks and propose new methodologies for pushing those limits further.

The main directions of this proposal lie on the study of the ultimate rate capability of a network in terms of the stable throughput region. Since we are approaching the 5G era, rate itself is not the most important metric. For this we also consider the newly defined metrics of the Age of Information, that captures the *freshness* of the transmitted information, and the Timely Throughput which evaluates both throughput and QoS for delay-constrained flows. At the same time the role of caching on network throughput can constitute a paradigm shift of foundational character for future wireless networks and could push further the performance limits of them.

3.1 Summarized plan (including theories and methods)

3.1.1 Stable Throughput Regions

In the context of bursty traffic, the ultimate rate capability of a network is defined in terms of the stable throughput region, that is, in terms of a set of traffic arrival rates for which the delays in the buffers do not grow to arbitrarily lengths. The interesting property of this stable throughput region is that it may be larger than the backlogged throughput region. The reason this may occur is that, unlike the backlogged case, the users of the network alternate between "busy" and "idle" states randomly and hence they do not require all the time a portion of the shared resource.

Preliminary attempts [2] (and the references therein) to evaluate the effect of burstiness on Shannon capacity have shown that, indeed, when traffic arrives randomly at a source it is possible to exceed the Shannon capacity of a single link under the backlogged source assumption. In other words, the randomness of "timing" creates the opportunity for additional information to be generated and transmitted. The intermittent contention for the common resource and the timing randomness can be combined to form an integrated view of the ultimate rate regions in a network. This requires the combined use of stability analysis and timing capacity analysis towards coding theorems as in [32].

In this part of the project we will characterize achievable throughput and stability regions of link-layer random access protocols over time-invariant physical layer channels modeled by the achievable rate regions. By random access communication, we mean that users determine their codebooks and communication rates individually (without cooperation). Our basic objective is to answer the question of how we should represent the fundamental physical layer coding support to link layer networking when users do not jointly determine their rates. Consider the following time-slotted transmission where in each time slot, a user encodes a certain number of data bits into a packet fitting within the time-slot. We consider coding within each time slot or each packet. Define the number of data bits per packet as the communication rate of a user in bits/slot, the value of which can change over different slots. Thus, the channel coding rate in the finite blocklength regime fits in our objective very well where the sources have random arrivals. For some classes of channels, have obtained new achievability and converse bounds on the coding rate for a given finite blocklength and error probability and also an asymptotic expression is derived [33].

The definition of *Stable Throughout ("Capacity")* with finite blocklength codes will be of a major importance, since it can provide insights on the code designing based on stochastic exogenous traffic and is a step further from the current traditional information theoretic research. **So, far the studies on finite blocklength codes do not consider bursty arrivals, we will be among the first to conduct research on this topic**.

The study of the impact of timing channels and finite blocklength codes on the stable throughput regions for the mentioned systems can be of major importance and will help to reduce the gap between traditional Information Theory and and Communication Networks. In this setup, the systems that we plan to investigate are the two-user ALOHA and the relay channel. We will also consider the Interference channel and the Two-User Degraded Gaussian Broadcast Channel since the applicant has some early progress on these cases [14, 13].

3.1.2 Age of Information and Timely Throughput

We will consider how age is affected by the sampling rate of the observed process and by the transmission paths that cause delay. Such paths can be modeled by queueing systems with parallel servers that correspond to the different networks over which the transmissions take place. The servers in these systems model the transmission channels and paths and can vary from simple M/M/1 to G/G/K models.

Clearly, the true age of an update may be an overestimate of its *effective age*. That is, if the observed process consists of highly correlated data/arrivals, then the frequency of transmission of updates can be significantly relaxed without affecting the freshness of the information.

We will investigate how a useful metric of effective age can be defined that takes into account the autocorrelation properties of the observed data/arrivals. Therefore, we will consider the correlation properties in the sources of interest and develop the concept of effective age, which is operationally the more significant variable for all applications. We will investigate the connection of age in the case of interacting queues. So far, the stochastic dominant systems technique does not seem able to be applied for the metric of Age of Information.

Furthermore, we will consider the effect of age on channel state information (CSI) in wireless transmissions. This is an amazingly overdue consideration that has been neglected so far. Delayed CSI can have a huge effect on wireless link performance. However, the key parameter for that is not the delay but the effective age of the CSI value.

Except age, Timely Throughput will be of our interest in this proposal. This newly defined metric appears to have a great potential for studying and modeling the ultimate limits of wireless networks. So far, the works on Timely Throughput have the major (and non-realistic) assumption of saturated traffic. The rigorous definition and study of ***Timely Stable Throughput*** will be of our interest in order to take into account the stochastic exogenous arrivals. New tools or modification of the existing ones in order to handle this metric will be proposed. Our study will be on simple system setups such as the two-user random access ALOHA network or the relay channel.

The analysis of simple models remains important to provide the first directions towards the design of systems that will be optimized for either Age of Information or Timely (Stable) Throughput.

3.1.3 Caching

In this part proactive, or context-aware, scheduling and resource allocation mechanisms leveraging the network information will be developed and studied. The benefits of proactive caching will be analyzed as a function of key network parameters such as memory size and energy consumption. We will address two fundamental and still open questions.

Modeling and anticipating users' demand. The majority of research [29, 30, 31] relies on the assumption of a fixed demand profile by the users however, this profile depends on time and location e.g., home users, travelers at the airport. It will be crucial to develop models that are able to learn and predict the users' demands based on the spatiotemporal characteristics which are slowly varying. This will result to an efficient operation of the caching network [34]. We plan to apply methodologies from Machine Learning to model and predict user demand profiles. Furthermore, the models for the demand profile will be used to devise optimal caching policies. At the user level, the achievable performance will be analyzed using information theory. At the network level, we will study the design of incorporating the new metrics of Age of Information and the Timely Throughput to further assist the update process of the demand profile.

Leveraging the properties of the wireless channel. So far, the most of the existing works have considered tractable but rather naive channel links that do not really capture the inherent properties of wireless channels. We will study the fundamental limits of caching networks by taking into account the underlying wireless channels characterized by fading, pathloss, interference. Here we will address the achievable rates rather than scaling laws in order to fully understand the benefits of the wireless caching networks in realistic setting. For example, a wireless device-to-device network, from the transmission viewpoint, falls in the class of Gaussian interference channels, for which, in certain conditions, treating interference as noise is near-optimal. The interplay between treating interference as noise-driven link scheduling and caching is a new and fundamental problem that we shall address within this proposal.

Towards the full understanding of wireless caching network in realistic settings, we aim to characterize the achievable throughput beyond scaling laws under various network architectures. These include: (i) the optimal dynamic user-helper association in Femtocaching model; (ii) the optimal D2D link scheduling in wireless D2D caching networks; (iii) the optimal cooperative multicasting, in the coded multicasting model, *so that the rate is no longer dictated by the user in the worst channel condition.*

This part is closely related with research in Sections 3.1.1 and 3.1.2. The outcomes on throughput with and without delay constraints coming from them will give new insights to the caching network design and performance.

3.2 Timetable

The proposed research project includes the research effort of the applicant for the following four years and at least one potential PhD thesis for a doctoral candidate which will be supervised by the applicant. In particular, the research project items presented above are expected to be completed according to the following schedule:

- Research Described in 3.1.1: Years 1-3
- Research Described in 3.1.2: Years 2-4
- Research Described in 3.1.3: Years 1-4

The tentative time schedule will be adjusted according to the results and difficulties. The items 3.1.1 and 3.1.2 will be completed mainly by the applicant. The PhD candidate will be expected to work on item 3.1.3 at a first stage and eventually to get involved with 3.1.2.

3.3 Implementation and Project Organization

Principal Investigator: The applicant will be the principal investigator and has extensive expertise in the topics proposed in this project and he is currently building on this expertise via his fruitful collaborations with researchers working on similar fields and problems.
PhD Candidate: The PhD candidate will first work on the Caching problem as described in 3.1.3. This will help the candidate gain better understanding on the more theoretical problems considered and gain expertise on analytical tools needed for targeting more advanced fundamental problems, such as the ones described in 3.1.1 and 3.1.2.

4 Significance

Wireless networks are ubiquitous in all domains of science and engineering and permeate many aspects of daily human life, such as transportation and communication. Thus, it is inevitable to develop a theoretical base that enables the designer to assess the achievable performance levels. However, it is also important to consider new technologies that will radically change the way wireless networks operate and will constitute a paradigm shift such as caching.

The contribution of this proposal is three-fold. The first is to reduce the gap between Information theory and Communication Networks; stable throughput region will play the major role for that. Secondly, latency and delay remain unsolved problems in wireless networks. However, in this project we will tackle these problems by utilizing new metrics that are relevant and at the same time different. The metrics of Age of Information and the Timely Throughput will be extended to the Effective Age and Timely Stable Throughput in order to capture efficiently the freshness of the transmitted information and the throughput under delay constraints. Finally, caching is expected to play a key role in the future's wireless networks by pushing their limits. The outcome will be a more efficient system of wireless content delivery which can have an unprecedented impact not only for the wireless customers but for operators, industry and manufacturers as well.

The scientific outcome of this work will result in a number of publications and presentations at leading international conferences and journals. Furthermore, through the results and collaborations, it will be possible to leverage the position of Linköping University as a key player in this field and as an attractive destination for young researchers and post-graduate students.

5 Preliminary results

The applicant has provided several preliminary results on the topics of the proposed project, starting from his PhD studies until now.

More specifically, the notion of partial cooperation was introduced in [15] and the stable throughput region was characterized. In that work was proven that partial (or probabilistic) cooperation provides better results than full cooperation or no cooperation at all. The effect of energy harvesting on stable throughout region in cooperative relay systems was studied in [18, 17]. The mentioned papers not only provide a step in connecting information theory and networking, by studying the maximum stable throughput region metric but also they tap the relatively unexplored and important domain of energy harvesting and assesses the effect of that on this important measure. The works [14, 13] consider the two-user interference channel and the two-user degraded Gaussian broadcast channel and the stable throughput region is obtained for the general case and for specific interference handling techniques as well.

Regarding Age of Information, at the time of writing this proposal there were published only 11 papers. The work in [25] investigates the Age of Information of Multiple Sources and a queue management technique is proposed. This technique drastically limits the need for buffering and can be applied in systems where the history of source status is not relevant. It is shown that this scheme results in significantly less transmissions compared to the standard M/M/1 queue model. Furthermore, it reduces the per source age of information, especially in settings not using queue management with high status update generation rates.

6 Independent line of research

I am currently employed in the frame of the European project FP7 SOrBet as a Marie Curie Fellow (IAPP). Within this project I have the academic freedom to work on topics such as network reliability, energy harvesting networks and network-level cooperative networks. Through my involvement in this project I enhanced my current skills and obtained new. Additionally, I participated in the organization of one summer school and one workshop in IEEE VTC 2015 Sping. My contract with this project ends on February 2016.

In the Mobile Telecommunications Group there are two EU Horizon 2020 projects, the WiVi2020 and the Act5G that are planned to start running on late 2015. Through these projects 3 PhD students will be hired and there is common field for this VR proposal and the aforementioned projects to establish collaboration. The applicant will play a key role in the mentioned projects by co-supervising the recruited students.

More specifically, WiVi2020 has strong connection with the part of this proposal which is described in 3.1.3, additionally Act5G will give the opportunity to the recruited students (including the recruited student of this project) to take advantage of the collaborations with the Bell Labs and the University of Maryland (in the frame of Act5G) to combine the academic excellence with the industrial one.

This project will give me the opportunity to conduct my independent line of research within the Mobile Telecommunications Group at the Science and Technology Department at Linköping University and solidify my position within Linköping University. Additionally, with the strong collaboration with major players from Academia and Industry it will be possible to leverage the position of Linköping University as a key player in this field and as an attractive destination for young researchers and post-graduate students.

7 Form of employment

I am currently employed as a Marie Curie Fellow (IAPP) at the Mobile Telecommunications Group at the Science and Technology Department at Linköping University. In the case that the project will be funded by VR, I will spend 75% of full time, while the remaining 25% will be devoted to other research and teaching duties. In addition, a PhD student will be recruited with 80% full-time employment in the project; the remaining 20% will be supported by teaching assistantships.

8 International and national collaboration

The applicant has built an excellent network of academic and industrial collaborators throughput Sweden, the rest of Europe, United States and Asia. More specifically, he completed his PhD studies in the Computer Science Department at the University of Crete under the supervision of Prof. Apostolos Traganitis. He spent one year in University of Maryland (split in three visits) as a visiting scholar collaborating with Prof. Anthony Ephremides. Between September 2012 and February 2014, he has worked as a postdoctoral researcher collaborating with Prof. Marios Kountouris at the Telecommunications Department at SUPELEC, France. Currently, he is a Marie Curie Fellow (IAPP) at the Mobile Telecommunications Group at the Science and Technology Department at Linköping University since March 2014 and collaborating with Prof. Di Yuan and Prof. Vangelis Angelakis. During summer of 2015 the applicant will be a Visiting Professor at the Singapore University of Technology and Design (SUTD) at the Wireless Networks and Decision Systems (WNDS) Group.

Throughput his academic career apart from the aforementioned collaborators he has on-going collaborations with other individuals; to name a few:

- Prof. Merouanne Debbah, Huawei, France / SUPELEC, France
- Prof. Henk Wymeersch, Chalmers, Sweden
- Prof. Giuseppe Durisi, Chalmers, Sweden
- Prof. Tony Quek, SUTD, Singapore
- Prof. Dong-Ku Kim, Yonsei University, South Korea
- Prof. Michal Pioro, Warsaw University of Technology, Poland / Lund University, Sweden
- Dr. Jeongho Jeon, INTEL Corporation, Santa Clara, USA

The applicant plans to continue his collaborations and also to establish new.

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Interdisciplinarity

My application is interdisciplinary

☐

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

Click here for more information

Scientific report

Scientific report/Account for scientific activities of previous project

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	Nikolaos Pappas	75

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	2019	Total
1	Applicant	Nikolaos Pappas	75	420,000	460,000	471,000	483,000	1,834,000
2	Other personnel without doctoral degree	PhD Student	80	266,000	296,000	302,000	307,000	1,171,000
	Total			686,000	756,000	773,000	790,000	3,005,000

Other costs

Describe the other project costs for which you apply from the Swedish Research Council. Enter the full amount, not in thousands SEK.

Premises

	Type of premises	2016	2017	2018	2019	Total
1	Local Remuneration	99,000	102,000	104,000	107,000	412,000
	Total	99,000	102,000	104,000	107,000	412,000

Running Costs

	Running Cost	Description	2016	2017	2018	2019	Total
1	Travel Costs	Travel Costs	135,000	150,000	155,000	160,000	600,000
	Total		135,000	150,000	155,000	160,000	600,000

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	686,000	756,000	773,000	790,000	3,005,000		3,005,000
Running costs	135,000	150,000	155,000	160,000	600,000		600,000
Depreciation costs					0		0
Premises	99,000	102,000	104,000	107,000	412,000		412,000
Subtotal	920,000	1,008,000	1,032,000	1,057,000	4,017,000	0	4,017,000
Indirect costs	349,000	383,000	392,000	401,000	1,525,000		1,525,000
Total project cost	1,269,000	1,391,000	1,424,000	1,458,000	5,542,000	0	5,542,000

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

Salary for the main applicant (Nikolaos Pappas): The above costs are approximately 75% of his salary. The rest 25% will be covered by Linköping University.

Salary for one (1) PhD Student: The above costs are approximately 80% of his salary including overhead. The rest 20% will be covered through teaching assistantships to the University by the PhD student.

Remuneration Costs: The ITN Department of LiU, where this application is hosted, applies 38% overhead to all cost categories. Personnel costs as topped with a further 64000 SEK/Full Time Equivalent for local facilities remuneration.

Travel Costs: Costs for attending conferences and also partially cover the visits of the mentioned collaborators.

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

1 Higher education qualifications

Jul. 2012 BSc Dept. of Mathematics, University of Crete, Greece
Sep. 2007 MSc (Telecommunications and Networks), Dept. of Computer Science, University of Crete, Greece
Feb. 2005 BSc Dept. of Computer Science, University of Crete, Greece

2 Doctoral degree

Aug. 2012 PhD (Telecommunications and Networks) Dept. of Computer Science, University of Crete, Greece
Thesis title: Network-Level Cooperation: Throughput, Stability and Energy Issues.

3 Postdoctoral positions

Sep. 2012 - Feb. 2014: Postdoctoral Researcher at the Telecommunications Depart., Supélec, France.
Mar. 2014 - Present: Marie Curie Fellow (IAPP) at the Dept. of Science and Technology (ITN), University of Linköping (LiU), Sweden.

4 Qualification required for appointments as a docent

The applicant will apply for the title, should the VR application is successful, so that he is awarded the title before the duties of the project commence.

5 Current position

Dept. of Science and Technology (ITN), University of Linköping (LiU), Norrköping Campus, Sweden.
Marie Curie Fellow (IAPP). Advisors: Prof. Di Yuan and Prof. Vangelis Angelakis.
Percentage of research: 100%

6 Previous positions and periods of appointment

Jun. 2015 - Jul. 2015 Visiting Professor at the Singapore University of Technology and Design (SUTD) at the Wireless Networks and Decision Systems (WNDS) Group.
Feb. 2005 - Aug. 2012: Research Assistant (MSc & Doctoral) of Telecommunications and Networks Laboratory at the Institute of Computer Science (ICS) of the Foundation for Research and Technology-Hellas (FORTH), Greece.
Sep. 2011 - Nov. 2011: Visiting Researcher at Institute of Systems Research (ISR) at the University of Maryland, USA.
Sep. 2010 - Feb. 2011: Visiting Research Associate at the Institute for Systems Research (ISR) at the University of Maryland, USA.
Sep. 2008 - Dec. 2008: Visiting Research Associate at the Institute for Systems Research (ISR) at the University of Maryland, USA.
Oct. 2002 - Dec. 2003: Undergraduate Research Assistant at the Computer Vision and Robotics Laboratory at FORTH-ICS.

7 Interruption in research

None.

8 Supervision

Manolis Ploumidis (co-supervised), 2012 - 2015, Computer Science Dept., University of Crete, Greece.
Ioannis Avgouleas (co-supervision),2014 - Present, Science and Technology Dept., Linköping University, Sweden.

9 Other merits of relevance to the application

9.1 Awards

2010-2013 Scholarship from the Greek Ministry of National Education and the National Strategic Reference Framework (NSRF), "HERACLEITUS II - University of Crete', (co-funded by the European Union and national resources) (45000 Euros) (Acceptance Rate <8%)
2005-2007 FORTH-ICS Scholaship for Master Students
2002-2003 FORTH-ICS Scholarship for Undergraduate students
2000 Represented Greece in the Mediterranean Mathematical Olympiad
2000 Honorable Mention at National Mathematical Olympiad "Archimedes" by Hellenic Mathematical Society
1999 Honorable Mention at National Mathematical Contest "Eucleides" by Hellenic Mathematical Society
1999 2nd Prize at National Mathematical Contest "Thales" by Hellenic Mathematical Society
1998 2nd Prize at National Mathematical Contest "Thales" by Hellenic Mathematical Society
1997 2nd Prize at National Mathematical Contest "Thales" by Hellenic Mathematical Society.

9.2 Invited Talks

Oct. 2012: "Wireless Network-Level Partial Relay Cooperation",
Host: Merouane Debbah, Alcatel Lucent Chair on Flexible Radio, SUPELEC, Paris, France.
Nov. 2012: "Optimal Utilization of a Cognitive Shared Channel with a Rechargeable Primary Node",
Host: Dong-Ku Kim, Yonsei University, Seoul, Korea.
Nov. 2013: "On the Maximum Stable Throughput Region of the Two-User Interference Channel",
Host: Dong-Ku Kim, Yonsei University, Seoul, Korea.
Dec. 2013: "On the Maximum Stable Throughput Region of the Two-User Interference Channel",
Host: Di Yuan, Linkoping University, Norrkoping, Sweden.
Nov. 2014: "On the maximum stable throughput regions: The two-user interference channel",
Host: Henk Wymeersch, Chalmers University of Technology, Gothenburg, Sweden.

9.3 Professional Activities

- **Currently serving as an Editor for the IEEE Communications Letters**
- **Served as a Track chair for the Wireless Telecommunications Symposium 2015 (WTS 2015)**
- **Served as a TPC member / Session Chair for the following conferences/workshops:**
  IEEE ITW 2013, ICC 2015, WCNC 2015, PIMRC 2014, 2015, WWIC 2014, 2015, SNOW 2014,2015, WTS 2015, VTC 2015-Spring Workshop, CAMAD 2014
- **Served as a reviewer for the following journals (selected):**
  IEEE JSAC, IEEE TMC, IEEE TWC, IEEE TCOM, IEEE Wirel. Comm. Letters, IEEE/KICS JCN, ELSEVIER PHYCOM, ELSEVIER COMNET, ELSEVIER COMCOM, Springer WINE, Springer Telec. Systems.
- **Served as a reviewer for the following conferences (selected):**
  IEEE ICC, GLOBECOM & Workshops, ISIT, EUSIPCO, PIMRC, WCNC, CAMAD, VTC, MILCOM

9.4 Teaching Activities

As the main lecturer in Science and Technology Department, Linköping University:
TNK104 Applied Optimization I, TNK105 Applied Optimization II.
Several graduate and undergraduate courses as a teaching assistant in Computer Science Dept. University of Crete.

Publication list

Accepted Publications for the last 8 years (in reverse chronological order). The five most relevant publications to this proposal are marked with (*).

1 Peer-reviewed original articles

J3 (*) **N. Pappas**, M. Kountouris, A. Ephremides, A. Traganitis, “Relay-assisted Multiple Access with Full-duplex Multi-Packet Reception", *accepted, to appear in IEEE Transactions on Wireless Communications, DOI:10.1109/TWC.2015.2408319, 2015*, arXiv:1310.2773[cs.IT].

J2 **N. Pappas**, A. Ephremides, A. Traganitis, “Stability and Performance Issues of a Relay Assisted Multiple Access Scheme with MPR Capabilities", Computer Communications, Volume 42, 1 April 2014, Pages 70-76, Elsevier. arXiv:1402.0729 [cs.IT].

J1 (*) **N. Pappas**, J. Jeon, A. Ephremides, and A. Traganitis, “Optimal Utilization of a Cognitive Shared Channel with a Rechargeable Primary Source Node", IEEE/KICS Journal of Communications and Networks (JCN) Special Issue on Energy Harvesting in Wireless Networks, Vol. 14, No. 2, Apr. 2012.

2 Peer-reviewed conference papers

C29 (*) **N. Pappas**, J. Gunnarsson, L. Kratz, M. Kountouris, V. Angelakis, “Age of Information of Multiple Sources with Queue Management", *IEEE International Conference on Communications (ICC) 2015, Jun. 2015.*

C28 I. Avgouleas, **N. Pappas**, V. Angelakis, “Cooperative Wireless Networking with Probabilistic On/Off Relaying", *IEEE 81st Vehicular Technology Conference (VTC Spring) Workshops, May 2015.*

C27 V. Angelakis, I. Avgouleas, **N. Pappas**, D. Yuan, “Flexible Allocation of Heterogeneous Resources to Services on an IoT Device", *IEEE Conference on Computer Communications (INFOCOM) Workshops, April 2015.*

C26 I. Avgouleas, **N. Pappas**, V. Angelakis, “Utilizing Multiple Full-Duplex Relays in Wireless Systems with Multiple Packet Reception", *19th IEEE International Workshop on Computer-Aided Modeling Analysis and Design of Communication Links and Networks (CAMAD), Dec. 2014.*

C25 M. Ploumidis, **N. Pappas**, A. Traganitis, “Delay Evaluation of a Throughput Optimal Flow Allocation Scheme for Random Access Wireless Multi-hop Networks", *19th IEEE International Workshop on Computer-Aided Modeling Analysis and Design of Communication Links and Networks (CAMAD), Dec. 2014.*

C24 Y. Li, **N. Pappas**, V. Angelakis, M. Pioro, D. Yuan, “Resilient Topology Design for Free Space Optical Cellular Backhaul Networking", *5th IEEE Workshop on Optical Wireless Communications (OWC’14), GLOBECOM 2014 Workshop, Dec. 2014.*

C23 **N. Pappas**, V. Angelakis, M. Kountouris, D. Yuan, A. Ephremides, "On the Age of Information of Multiple Sources Under a Simple Queue Management Technique", *1st KuVS Workshop on Anticipatory Networks, Stuttgart, Germany, Sep. 2014.*

C22 M. Kountouris and **N. Pappas**, “Approximating the Interference Distribution in Large Wireless Networks", *11th International Symposium on Wireless Communication Systems (ISWCS 2014), Special Session on Advanced Small Cells for Future Systems, Barcelona, Spain, Aug. 2014.*

C21 **N. Pappas** and M. Kountouris, “Throughput of a Cognitive Radio Network under Congestion Constraints: A Network-Level Study", *9th International Conference on Cognitive Radio Oriented Wireless Networks (CROWNCOM), Oulu, Finland, Jun. 2014*.

C20 **N. Pappas** and M. Kountouris, “Performance Analysis of Distributed Cooperation under Uncoordinated Network Interference ", *2014 IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP), Florence, Italy, May 2014*.

C19 M. Ploumidis, **N. Pappas**, and A. Traganitis, “Throughput Optimal Flow Allocation on Multiple Disjoint Paths for Delay-Bounded Wireless Multi-hop Networks", *9th IEEE Broadband Wireless Access Workshop (BWA), Globecom 2013 Workshop, Dec. 2013*.

C18 (*) **N. Pappas**, M. Kountouris, J. Jeon, A. Ephremides, and A. Traganitis, “Network-Level Cooperation in Energy Harvesting Wireless Networks", 1st IEEE Global Conference on Signal and Information Processing (GlobalSIP) 2013, Symposium on Energy Harvesting and Green Wireless Communications, Dec. 2013.

C17 (*) **N. Pappas**, M. Kountouris, and A. Ephremides, “The Stability Region of the Two-User Interference Channel", *IEEE Information Theory Workshop 2013 (ITW 2013), Sep. 2013*.

C16 **N. Pappas**, M. Kountouris, A. Ephremides, and A. Traganitis, “On the Stability Region of a Relay-Assisted Multiple Access Scheme", *IEEE Information Theory Workshop 2013 (ITW 2013), Sep. 2013*.

C15 M. Kountouris and **N. Pappas**, “HetNets and Massive MIMO: Modeling, Potential Gains, and Performance Analysis", IEEE APWC 2013, IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications, Sep. 2013.

C14 M. Ploumidis, **N. Pappas**, and A. Traganitis, “A Flow Allocation Scheme for Maximum Throughput for Random Access Wireless Multi-hop Networks", Fourth Nordic Workshop on System & Network Optimization for Wireless, Ylläs, Finland, Apr. 2013.

C13 G. Papadimitriou, **N. Pappas**, A. Traganitis, “Performance Issues of Multiple-Relay Cooperation", IEEE ICC 2013 - Wireless Networking Symposium, Budapest, Hungary, Jun. 2013.

C12 M. Ploumidis, **N. Pappas**, V. Siris, A. Traganitis, “Evaluating Forwarding Schemes Exploiting Path Diversity and Degrees of Redundancy in a Realistic Wireless Environment", IEEE 17th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD), Sep. 2012.

C11 (*) **N. Pappas**, J. Jeon, A. Ephremides, and A. Traganitis, “Wireless Network-Level Partial Relay Cooperation", IEEE International Symposium on Information Theory (ISIT), Cambridge, MA, USA, Jul. 2012.

C10 J. Jeon, **N. Pappas**, A. Ephremides, and A. Traganitis, “Stability of a Network with Energy Harvesting Capability", Third Nordic Workshop on System & Network Optimization for Wireless, Trysil, Apr. 2012.

C9 **N. Pappas**, J. Jeon, A. Ephremides, and A. Traganitis, “Optimal Utilization of a Cognitive Shared Channel with a Rechargeable Primary Source Node", IEEE Information Theory Workshop 2011 (ITW 2011), Oct. 2011.

C8 **N. Pappas**, A. Ephremides, A. Traganitis, “Relay-Assisted Multiple Access with Multi-Packet Reception Capability and Simultaneous Transmission and Reception", IEEE Information Theory Workshop 2011 (ITW 2011), Oct. 2011. [Extended version In arXiv:1105.0452 [cs.IT]].

C7 **N. Pappas**, A. Ephremides, A. Traganitis, “Stability and Performance Issues of a Relay Assisted Multiple Access Scheme with MPR Capabilities", 9th Intl. Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), May 2011.
[Invited for fast track journal publication in Elsevier Computer Communications]

C6 M. Ploumidis, **N. Pappas**, V. Siris, A. Traganitis, “Short Term Wireless Channel State Prediction Using Markov Models and Supervised Learning", Euro-NF International Workshop on Traffic and Congestion Control for the Future Internet, Mar. 2011.

C5 **N. Pappas**, A. Ephremides, A. Traganitis, “Performance Issues of a Relay Assisted Multiple Access Scheme", The Second Nordic Workshop on System and Network Optimization for Wireless, Mar. 2011.

C4 **N. Pappas**, A. Traganitis, A. Ephremides, “Stability and Performance Issues of a Relay Assisted Multiple Access Scheme", IEEE Globecom 2010 - Wireless Networking Symposium, Dec. 2010.

C3 **N. Pappas**, V. Siris, A. Traganitis, “Delay and Throughput of Network Coding with Path Redundancy for Wireless Mesh Networks", Third Joint IFIP Wireless and Mobile Networking Conference, Oct. 2010.

C2 **N. Pappas**, V. Siris, A. Traganitis, “Path Diversity Gain with Network Coding and Multipath Transmission in Wireless Mesh Networks", IEEE International Symposium on a World of Wireless Mobile and Multimedia Networks (WoWMoM), Jun. 2010.

C1 **N. Pappas** and A. Traganitis, “On the alphabet size of a linear network code", 5th International Conference on Broadband Communications, Networks and Systems, (BROADNETS), Sep. 2008.

3 Journals submitted/under revision with Arxiv Pre-prints

P6 G. Papadimitriou, **N. Pappas**, V. Angelakis, A. Traganitis, “Network-Level Performance Evaluation of a Two-Relay Cooperative Random Access Wireless System", *Submitted to Elsevier Computer Networks, Mar. 2015*, [In arXiv:1406.5949v2 [cs.NI]].

P5 (*) **N. Pappas**, M. Kountouris, J. Jeon, A. Ephremides, and A. Traganitis, “Effect of Energy Harvesting on Stable Throughput in Cooperative Relay Systems", *Submitted to IEEE Transactions on Information Theory, Feb. 2015*, , [In arXiv:1502.01134 [cs.IT]].

P4 (*) **N. Pappas** and M. Kountouris, “The Stability Region of the Two-User Degraded Gaussian Broadcast Channel", *Submitted to IEEE Transactions on Vehicular Technology, Jan. 2015*, arXiv:1501.06267[cs.IT].

P3 M. Ploumidis, **N. Pappas**, A. Traganitis, “TOFRA: Throughput Optimal Flow Rate Allocation with Bounded Delay for Random Access Wireless Mesh Networks",*Under major revision in IEEE Transactions on Vehicular Technology, Dec. 2014*, [In arXiv:1406.6304 [cs.NI]].

P2 Y. Li, **N. Pappas**, V. Angelakis, M. Pioro, D. Yuan, “Optimization of Free Space Optical Wireless Network for Cellular Backhauling", *Under minor revision in IEEE JSAC Special Issue on Optical Wireless Communication, Mar. 2015*, [In arXiv:1406.2480[cs.NI]].

P1 M. Ploumidis, **N. Pappas**, V. Siris, A. Traganitis, “On the Performance of Network Coding and Forwarding Schemes with Different Degrees of Redundancy for Wireless Mesh Networks", *Under major revision Computer Communications Journal, Elsevier, Mar. 2015*, arXiv:1309.7881[cs.NI].

CV

Name: Nikolaos Pappas	**Doctorial degree:** 2012-08-24
Birthdate: 19820918	**Academic title:** Doktor
Gender: Male	**Employer:** Linköpings universitet

Research education

Dissertation title (swe)

Dissertation title (en)

Network-Level Cooperation: Throughput, Stability and Energy Issues

Organisation	Unit	Supervisor
University of Crete, Greec Not Sweden - Higher Education institutes		Apostolos Traganitis

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
10202. Systemvetenskap, informationssystem och informatik (samhällsvetenskaplig inriktning under 50804)		2012-08-24

Publications

Name: Nikolaos Pappas	**Doctorial degree:** 2012-08-24
Birthdate: 19820918	**Academic title:** Doktor
Gender: Male	**Employer:** Linköpings universitet

Pappas, Nikolaos 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.