Application

2015-03-31

2015-05220 **Kihl, Maria** **NT-14**

Information about applicant

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Information about application

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

Type of grant: Projektbidrag

Focus: Fri

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Project title (english): Power consumption modelling and optimization of content distribution architectures

Project start: 2016-01-01

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Funds applied for

Year:	2016	2017	2018	2019
Amount:	916,000	932,000	952,000	967,000

Descriptive data

Project info

Project title (Swedish)*

Modellering och optimering av energiförbrukning för digital mediadistribution

Project title (English)*

Power consumption modelling and optimization of content distribution architectures

Abstract (English)*

The heavily increasing consumption and production of digital media content via Internet and cellular networks will create large digital carbon footprints that will, some day, have to be delt with. Power consumption optimization on all levels in the distribution architectures will be a major challenge. The current Internet content distribution architectures, incorporating, for example, data centers, content delivery networks (CDNs) and home equipment consitute large complex engineering systems with many involved actors.

At the moment, very little research is focused on the holistic understanding of power consumption in content distribution architectures. In order to propose and evaluate power-optimized architectures, accurate models are required that can capture the dominant power-consumption dynamics in the eco-system of content distribution. However, the current state-of-the-art power consumption models are not consistent and contain many flaws. Therefore, fundamental research is required to understand how digital content consumes power when stored and transported in these systems, in order to facilitate the development of energy saving and optimization solutions that the future Internet requires.

The main objective of this project is, therefore, to fill this research gap and obtain a holistic understanding of the fundamental power consumption dynamics of Internet content distribution architectures, also including cellular networks. In this project, we will identify the dominant end-to-end power consumption dynamics in today's content distribution architectures. Further, we will formulate a new scientific framework, including a generic power consumption model, for how to estimate power consumption of digital media content in both fixed and cellular networks. Also, we will propose and validate power-optimized content distribution architectures that can be used as benchmarks in the future Internet. All models and solutions will be validated with measurements in our testbed as weil as with our industry connections.

The proposed research project targets a crucial topic with both high academic and industrial importance and interests, namely the sustainability of the future Internet architectures. The research partners in this project works in several research communities, covering both autonomic computing and networking, and in both national and international projects with related activities. The project will facilitate initiatives as, for example, Greenpeace's Clean Energy Index, which already has changed major companies' sustainability strategies.

Popular scientific description (Swedish)*

Vi spenderar allt mer tid på nätet och användandet av streaming och andra mediatjänster ökar kraftigt. Bara Youtube har en miljard unika besökare varje månad. I USA består ca 50% av Internet-trafiken till hushållen av data från Netflix och Youtube. Mycket av denna trafik kommer i framtiden gå i de mobila näten där nätkapaciteten är mer begränsad än i de fasta näten.

Vårt Internet-användande kräver därför mer och mer energi. Inte bara för att överföra data utan även för att lagra data. Till exempel kommer bara Facebooks nya datacenter i Luleå att dra lika mycket energi som tiotusentals svenska villor. Flera av de stora Internet-jättarna, tex Google, Apple, Amazon och Facebook har inte haft miljön i fokus när de byggt sina datacenter. Många av dem är till exempel placerade i North Carolina där kolkraften och marken är billig. Därför är de digitala mediatjänsterna med och bidrar till ett stort koldioxidfotspår som vi kommer att få ta hand om i framtiden.

Digital mediadistribution sker via en kedja av datacenter, nät och mellanlagriingssystem (caching). Det är ett komplext system med många olika aktörer, både aktörer som producerar, äger och tillhandahåller innehållet, samt aktörer som transporterar innehållet. För att förstå hur system för mediadistribution ska byggas på ett energieffektivt sätt krävs det generiska modeller och studier av hur olika arkitekturer påverkas av användarmönster. Tyvärr är dagens modeller och lösningar för optimerad energiförbrukning för enkla och i många fall fel. Det krävs därför grundforskning för att förstå energiförbrukningen för mediadistribution över Internet och mobila nät.

I detta projekt kommer vi först att identifiera vad som kostar energi i dagens system för mediadistribution samt hur mycket energi olika typer av innehåll kostar när det lagras och transporteras över Internet och mobila nät. Sedan kommer vi att utveckla ett ramverk för hur man ska modellera energiförbrukning av arkitekturer för mediadistribution. Ramverket kommer att innehålla en generisk nätmodell samt en komponent-baserad modell för energiförbrukning som ska kunna användas för analys och optimering av olika arkitekturer och lösningar. Dessutom kommer vi att använda ramverket för att undersöka hur mediadistribution ska göras på ett så energieffektivt sätt som möjligt. All forskning kommer att genomföras i nära samarbete med våra industrikontakter inom området för att vi ska kunna garantera att modeller och resultat är korrekta och genomförbara i verkliga system. Resultaten från projektet kommer att kunna medverka till miljösatsningar som tex Greenpeace Clean Energy Index samt designen av framtidens hållbara Internet.

Project period

Number of project years*

4

Calculated project time*

2016-01-01 - 2019-12-31

Classifications

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

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

SCB-codes*	2. Teknik > 202. Elektroteknik och elektronik > 20204. Telekommunikation

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

Keyword 1*

Power consumption

Keyword 2*

Content distribution architectures

Keyword 3*

Sustainabililty

Keyword 4

Optimization

Keyword 5

Internet

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*

Vi anser att projektet inte kräver några etiska överväganden.

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

Power consumption modelling and optimization of Content distribution architectures

Purpose and aims

Recent studies have shown that Information and Communication Technology (ICT) systems are responsible for as much CO_2 output that caused by the global airline industry [1, 2]. Data centers consume ever greater amounts of power. For example, the recently built Facebook data centre in Luleå will, annually, consume as much power as it would take to heat tens of thousands of Swedish homes. At the same time there are predictions that online TV and video will be watched in at least 520 million homes by 2018, which is an increase of almost 300% since 2010 [3]. Already today, Youtube has more than 1 billion unique users every month [4]. In the US, about 50% of the downstream Internet traffic comes from Netflix and Youtube [5]. Also, new applications are emerging, where a recent example is Twitch.tv [6], which hit the networks with previously unpredicted traffic. Much of this traffic will be transported by cellular networks, where traffic has totally exploded the last years [7].

The heavily increasing consumption and production of digital media content will create large digital carbon footprints that will, some day, have to be dealt with. Power consumption optimization on all levels in the distribution architectures will be a major challenge. Current Internet content distribution architectures, incorporating, for example, data centers, content delivery networks (CDNs) and home equipment, consitute large complex engineering systems with many involved actors.

At the moment, very little research is focused on the holistic understanding of power consumption in content distribution architectures. In order to propose and evaluate power-optimized architectures, accurate models are required that can capture the dominant power-consumption dynamics in the eco-system of content distribution. However, the current state-of-the-art power consumption models are not consistent and contain many flaws. Therefore, fundamental research is required to understand how digital content consumes power when stored and transported in these systems, in order to facilitate the development of energy saving and optimization solutions that the future Internet requires.

The main objective of this project is, therefore, to fill this research gap and obtain a holistic understanding of the fundamental power consumption dynamics of Internet content distribution architectures, including cellular networks. The project will

- **Identify** the dominant end-to-end power consumption dynamics in today's content distribution architectures.
- **Formulate** a new scientific framework, including a generic power consumption model, for how to estimate power consumption of digital media content in both fixed and cellular networks.
- **Propose and validate** power-optimized content distribution architectures that can be used as benchmarks in the future Internet.

In real systems, the sustainability aspects will of course need to be merged with other aspects, such as expenditure and operation costs, business models and latency requirements. However, with this project, sustainability can become a key factor in the design of the future Internet.

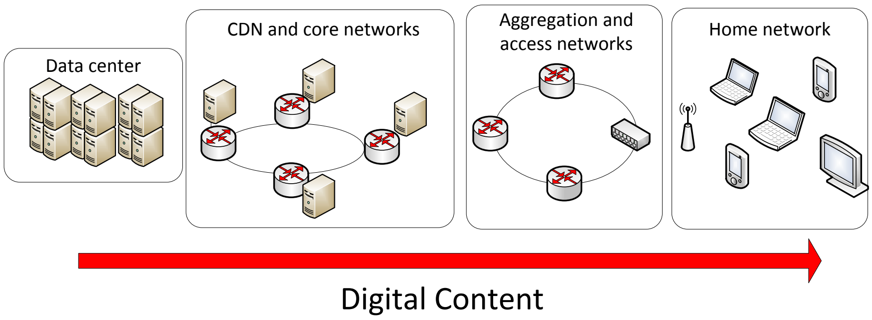

Figure 1: A schematic illustration of a content distribution architecture.

Survey of the field

The main objective of a content distribution architecture is to move digital content, e.g. videos, from a content provider to users, see Figure 1 for a schematic illustration. In today's commercial systems, content is often stored in back-end data centers, and then distributed via some type of Content Delivery Network (CDN) solution, essentially a network of cache servers that will place popular content closer to the users in order to save network capacity and decrease latency. A CDN is both a network infrastructure and a business model, since content providers will buy cache storage and distribution from a CDN provider. The users connect to the Internet through access and aggregation networks.

The optimization of content placement constitutes a complex research problem that has attracted much research from both academia and industry over many years. The current gigantic world-wide CDN-architectures, like Akamai, Google, and Youtube, with billions of content objects and users, have inspired many researchers interested in optimization of large distributed systems. See, for example, [8, 9] for overviews.

De-facto standard power consumption model

Power optimization of content distribution architectures has attracted much less attention. Power optimization adds one more level of complexity, and requires knowledge of the underlying network architectures. Most papers focusing on power consumption optimization in content distribution architectures use generic network models as illustrated in Figure 2 (or similar), see for example [10, 11, 12]. Each household connects to the Internet through an access network. Aggregation networks aggregate households' traffic from the access network into higher capacity links through Ethernet switches. Finally, the aggregation network is connected to core networks through edge routers. The core networks consist of core routers, which are interconnected by optical fiber links. The data centers connect directly to the core network through an edge router. Within each data center, there are content servers, data storage equipment, and local area networks (LANs). CDNs are most often only modelled as cache servers distributed in the core and/or aggregation networks. Architectures without caches are sometimes called Data Center Networks (DCNs).

A survey on some power-saving technques for CDNs and DCNs can be found in [13]. Most current work on power optimization of content distribution architectures is based on a power consumption model originally proposed by Baliga et. al [14, 15, 11]. The model estimates the energy (E_d), measured in Watt-hours, for storage and transmission of a movie of size B bits that is replicated in R data centers and downloaded D times. The model is given by:

$$E_d = \frac{B}{3600}\left(\frac{3P_{ES}}{C_{ES}} + \frac{P_G}{C_G} + \frac{2P_{PE}}{C_{PE}} + \frac{(H+1)P_C}{C_C} + \frac{HP_{WDM}}{C_{WDM}} + \frac{P_{SR}}{C_{SR}}\right) + \frac{BR}{D}\left(\frac{P_{SD}}{C_{SD}}\right) \quad (1)$$

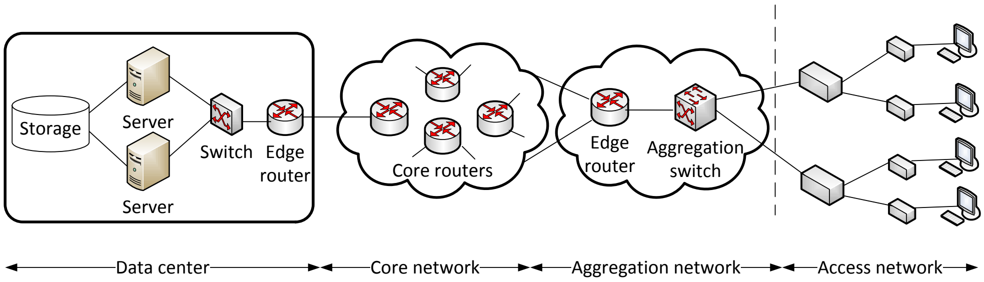

Figure 2: Generic network architecture.

P_{ES}, P_G, P_{PE}, P_C, P_{WDM}, P_{SR} and P_{SD} are the power consumption of the Ethernet switches, gateway routers, provider edge routers, core routers, WDM equipment, content servers and storage disks, respectively. C_{ES}, C_G, C_{PE}, C_C, C_{WDM}, C_{SR} are the capacities of the corresponding equipment in bits/sec and C_{SD} is the capacity of the storage disks in bits. H is the number of core network hops.The factor of three for Ethernet switches and factor of two for provider edge routers is used to include the equipment in the metro network and in the data center. The original model also includes some factors for redundancy that have been omitted above to make the model more readable. In papers investigating architectures with CDN caches, these caches are usually modelled as smaller storage nodes (disks) spread in the network.

Current work and results

In [14], which originally proposed (1), Baliga *et. al* estimate the power consumption of the access network, aggregation network and core network separately. Their results show that the majority of the network power consumption is generated by the access network. Based on this result, Baliga *et. al* in [15] focus only on the access network. However, none of their work considers either the storage power consumption or the total energy consumption in terms of traffic load and time. Their follow-up work in [11] estimates power consumption for a Video-on-Demand (VoD) service. The calculation contains both storage and transmission power consumption in a network with data centers. However, in this work, the power consumption in the access network is excluded. Their results show that popular videos should have more replicas throughout the network to make sure that the content is closer to the users. Also, their results show that P2P is not efficient for distributing content with high demand. In [12], also using the power consumption model (1), Jayasundara *et. al* conclude that popular content should be placed closer to the users in order to optimize power consumption for the content distribution architecture.

If popular content should be placed closer to the users, there must be a dynamic content placement scheme deciding where content objects should be placed in order to optimize the power consumption of the whole system. In [16, 10], Mandal *et. al* extend the work in [12] by proposing an Integer Linear Programming (ILP) approach to choose the content placement for each video in order to minimize the power consumption for the whole network. In [16], at least 11% of the power consumption can be saved when 25% of the backbone nodes are used as cache (i.e. CDN) comparing to a network with only one data center (i.e. DCN). Further, 18% of the energy can be saved if all the backbone nodes are able to cache (i.e. CCN). However, in [10] they change the hardware and thereby the power saving is only 5% even though they use the same ILP approach and the same number of nodes in the backbone network are used as caches.

Some papers have compared conventional DCN and CDN architectures with P2P architectures. In [17], Feldmann *et. al* use a variant of the power consumption model (1) to compare the power consumption of DCN, CDN and P2P networks, with VDSL as access network. Their results show that CDN consumes the least energy, since in P2P architectures the power consumption migrates from the core network to the end users, which means that the total power consumption is not reduced, which essentially confirms the results in [11]. This result is, however, contradicted in [18], where Mandal *et. al*, propose a hybrid CDN-P2P architecture and compare it with a conventional CDN. Here, it is shown that if peers can share popular content with 1-2 hours duration, this hybrid architecture can save up to 30-40% energy compared to a CDN architecture. However, this work only considers the transmission power consumption in the core network, and not the power consumption of the end users that store the content.

In [19], Valancius *et. al* proposes Nano data centers (NaDa), which use home gateways as nano data servers (i.e. cache servers), which means that it is essentially a P2P architecture. The paper presents a thorough investigation on the potential energy savings in such an architecture, using a simplified variant of (1). Comparing with conventional DCNs, NaDa are shown to save 20-30% energy consumption. However, in their model, the power consumption of home gateways is ignored, with the motivation that they are already in operation. Therefore, it is obvious that a NaDa-based architecture will consume less energy than a DCN.

Further, Content-centric networks (CCNs), also called Information Centric Networks (ICN), where network devices like core routers and edge routers are used as cache servers, have attracted much attention in recent years. For example, in [20], Choi *et. al* uses a variant of (1) to show that CCNs use less energy than CDNs. However, in their investigation, they do not use comparable hardware for the two architectures. For example, CCNs use low-energy SSD disks whereas traditional CDNs use high-energy hard drives, which makes it obvious that CCNs will consume less energy than CDNs. In [21], Araujo *et. al* investigate the energy effects of in-network caches. The optimization problem is formulated as an MILP problem, with an underlying model similar to (1) to find the optimal placement of network caches. They show that the most energy-efficient solution is to use an optimized CCN architecture combined with a CDN. However, the model is very simplified to make it fit as an MILP problem and only includes power consumption in the core network, which means that the power consumption of data centers is ignored.

In a another recent paper [22], Modrzejewski *et. al* investigate cache placement within an Internet Service Provider (ISP) network, which is somewhat similar to CCNs. They propose a power consumption model that includes the cost of reading and writing content to/from a cache, which is somewhat new in comparison with other papers. However, their main conclusion is quite obvious, essentially that network caches will save energy.

As mentioned before, most papers are based on the power consumption model (1) or variants of it. However, authors have a tendency to ”skip” some parts of the model that do not suit their interests, making their results unable to be compared with other papers. Further, the papers usually totally ignore all research on data center power optimization. The power efficiency of data centers is often represented with a PUE value (Power usage efficiency value, used to model the power overhead corresponding to cooling etc.) that is too high for modern data centers. This means that data center storage is often more energy costly in the papers than in reality. This could partly explain why decentralized P2P- and CCN-solutions often are found to be more energy-efficient than centralized solutions. Further, few of the papers above use real data traces in their work. Instead, they use highly simplified static workloads that do not take into account any spatial or temporal variations. For example, content caching is not static, since new content is continously published, and these cache updates may contribute considerably to the power consumption in decentralized solutions, where content must be replicated numerous times. Finally, none of the papers consider cellular networks, only traditional fixed network infrastructures. There has been considerable work on power consumption in cellular networks, mostly aimed at green cellular network architectures, see for example [23]. However, none of these papers relate to content distribution.

Preliminary results

The main applicant has a solid background in performance modelling of Internet architectures and content demand patterns of digital media, some recent papers are for example, [MK10, MK18, MK19, MK23][1]. Also, she has long experience of server-based systems (for example web server systems and clouds) [MK3, MK9, MK11, MK27].

Most of the work has been focused on analysing user content demand patterns based on traffic measurements in real networks. More recently, the work has continued with investigating caching potential of content from, for example, Youtube [MK18, MK20, MK23], Facebook [MK19], and TV4 [MK10, MK14]. The work has been performed in close cooperation with Acreo Swedish ICT, Ericsson AB, and TV4 in several national and European research projects. This work has formed the fundamental knowledge of content distribution architectures that is needed in order to understand the power optimization challenges in these systems.

Recently, in the Vinnova project EFRAIM (Eco-system for future media distribution) and the Celtic-Plus project NOTTS (Next-generation over-the-top services), we have performed some preliminary work on power consumption modelling of content distribution architectures, mainly collecting the current state-of-the-art and defining the challenges and research problems. Some of the work has been presented in a bachelor thesis [24] and a master thesis [25]. Also, we have published a paper on energy-saving potential in access networks [MK15].

Currently, we have performed some preliminary work to understand the dynamics of the de-facto standard power model (1) when using it on real data traces. The dynamics of (1) for a certain network configuration are essentially only decided by the size of the content objects and the number of downloads per object. The model assumes a static workload, and therefore, we have developed a time-dependent power consumption model in order to evaluate the effects when using real content demand patterns. The model is based on (1), and the data trace comes from the dataset used in [26], which is based on a real commercial TV-on-demand service. We have used a network configuration similar to Figure 2 with one data center, one network cache placed at the end of the aggregation network, and 32.000 users. The cache can store maxiumum 500 programs (content objects) and the content is replaced dynamically with a standard Least-Recently Used (LRU) algorithm. For simplicity, we have chosen the same power efficiency parameters as in [12, 16, 17]. Also, we only estimate the power consumption of content distribution, in order to evaluate if a network cache saves transport and storage costs when using real user content demand patterns. Figure 3 shows the average diurnal power consumption for the system with and without the network cache. As can be seen, a network cache placed at the end of the aggregation network is estimated to save about 50% energy during peak hours compared to an architecture without a cache. However, during non-peak hours, the network cache will only save a limited amount of energy compared to a system without a cache. This means that the cache could essentially be turned off and thereby saving energy during non-peak hours.

Project description

The main objective of this project is to achieve a holistic understanding of the power consumption of digital content distribution over the Internet. In order to obtain models and architectures that have a basis in reality, it is also necessary to a have a good knowledge of the commercial systems deployed. Therefore, we will always work in close cooperation with our relevant industry research connections. Our industry contacts will ensure that the models and parameters we propose and use are accurate and suitable for real systems. They can provide us with the deep technical knowledge of architectures and systems that is required for the success of this project.

[1] MKxx refer to papers in Maria Kihl's publication list

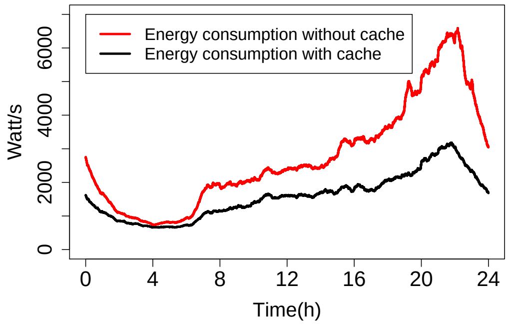

Figure 3: Energy consumption during one day.

End-to-end power consumption dynamics

In the first part of the project, we will identify the dominant power consumption dynamics when storing and transporting content on the Internet. The objective is to obtain a fundamental understanding of how content objects, for example, videos, consume power when stored in data centers and caches and transported in networks in order to propose an accurate power consumption framework in the second part of the project. We will consider both "traditional" client-server based applications, as today's Video-on-demand systems, as well as the emerging applications based on high-quality user-generated content, for example Twitch.tv [6], where data centers may not be the origin of the content. Part of this work will be based on the latest literature on power consumption of server systems and network equipment, see for example [27, 28]. Also, we will build a testbed and perform our own measurements in our network lab, where we currently host network equipment and an up-to-date server cluster as part of our other research projects (see below). Also, as mentioned above, we will work closely with our industry connections, who develop, deploy and host commercial systems for the whole ecosystem of content distribution. Below, we present some of our initial ideas on how networks, storage and transport contribute to end-to-end power consumption. During the project, we will further investigate these areas and validate our results with our industry connections and by performing measurements in our testbed.

Networks. Several studies have shown that the core and aggregation networks account for only a small part of the total end-to-end power consumption in fixed networks, see for example [2]. Therefore, a generic power consumption framwork for fixed networks may actually ignore several parts, since they will not be a dominant factor when optimizing the power consumption in content distribution architectures. Also in cellular networks, the core networks can probably be ignored, since they are usually the same or similar as in fixed networks (high speed optical networks). However, the access networks with base stations would probably need to be taken into account, since these have been identified as considerable power consumers [2].

Storage. Several studies have argued that data centers and home terminals are the dominant factors when considering power consumption in ICT systems [2]. Therefore, we believe that it is crucial to identify how content consumes power when stored in data centers and caches. However, although big companies are actively working to reduce the energy consumption of data centers, the research on the topic is still in its early stages [27]. Also, there is very little research aimed at content storage. Further, it is rather difficult to find solid studies on cache server power consumption. Therefore, the proper modelling of storage power consumption is still an unsolved research question. We have previously performed some fundamental research on the modelling of database servers [MK24, MK34], where one conclusion was that write operations are much more processing intensive than read operations. And if processing can be translated to power consumption, this result would be in line with, for example, [22], which would imply that the dynamic replacement of content in caches would be an important power consumption factor.

Transport. In the de-facto standard power consumption model (1), there is a linear dependence between the power consumption and the number of transported bits, which implies that network devices have a load-proportional power consumption. However, recent research argue that this not true, at least not for fixed networks. In, for example, [28], it is shown that for modern network devices in the Internet (e.g routers and switches), power consumption is based on two components, a constant baseline component and a load-dependent component, where the baseline power consumption is as much as 80-90% of the maximum power consumption when the network device is fully loaded. Following these results, transport power consumption in fixed networks is essentially only dependent on the number of network devices, not the number of transported bits. For cellular networks there is a major lack of research, and the few studies that exist, for example [29, 30], are not focused on the transport of content.

Power consumption framework

In this part of this project, we will use the identified dynamics from the previous part and formulate a new power consumption framework, which includes a complete power consumption model for content distribution architectures based on a generic network model.

Networks The generic network models for fixed networks used in most papers, as illustrated in Figure 2, are probably accurate enough for power consumption analysis. There are, of course, numerous ways to build a physical network, however, we need a generic network model for this work. The network model should incorporate different access technologies, since they will have different impacts on holistic power consumption. For cellular networks, there is a need to develop a proper network model suitable for power consumption analysis. Here, we will extend and modify previously proposed network models. For example, we currently have research activities focusing on so called telco clouds [MK11] where we have developed a simulation model for cloud infrastructures distributed in the cellular network infrastructures. These systems share the same underlying network models that we will use in this project.

Power consumption model. We propose a component-based model, as illustrated in Figure 4, where each part of the content distribution eco-system is modelled separately in order to maximize usage flexibility and facilitate different architectures and network technologies. We will essentially aim for ”plug-in” components, where each component can be developed independent of the other components. If one component is changed due to new technologies or standards, it will be easy to modify it and then seamlessly integrate it in the model. Also, this would facilitate development and implementation in, for example, Modelica [31], in which we have long experience and competence. An example of one topic that we will investigate is the power cost of replication and transcoding of content. Today, video content is usually transcoded multiple times in order to fit various video coding formats and client platforms. This transcoding can be performed in the back-end data center, or ”on-the-fly” in the cache servers. None of the previously published models incorporate transcoding. We will investigate how transcoding should be modelled in order to obtain proper power consumption estimates. Also, we will validate our proposed model and its parameters will be validated both with measurements in our testbed and in close cooperation with our industry contacts.

Power-optimized content distribution architectures

With a holistic understanding of the dominant power consumption dynamics in the eco-system of content distribution, and a scientific power consumption framework, the final part of the project will be to use the framework to develop power-optimized content distribution architectures that can be used as benchmarks in the future Internet. Power-optimized architectures can be found by formulating the power consumption model as an optimization problem, where the cost function corresponds to power consumption of storage and transport of content objects

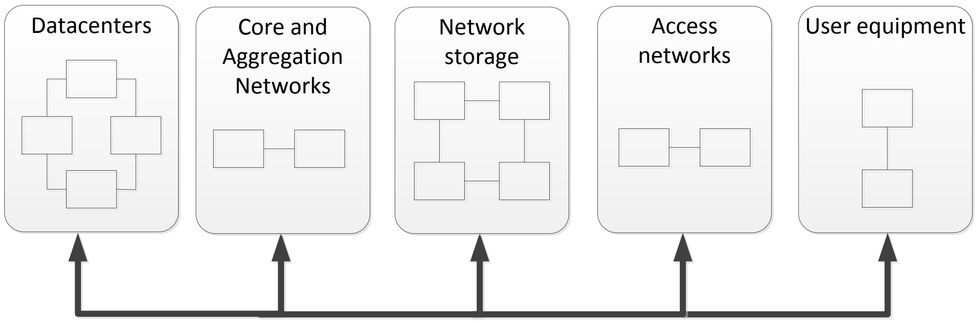

Figure 4: Illustration of the component-based power consumption model. The arrows represent relationships and signal flows between components.

according to a given content demand pattern and application constraints. For this part of the work, we will use the data traces available to us via our industry contacts and other research projects (see below).

Our initial ideas in this part of the project mostly concern the power cost of distributed storage. Resouce-optimized data centers are probably the most power efficient way to store content. Smaller cache servers or user equipment will never have as low Power Usage Effectiveness (PUE). Also, distributed storage means increased transcoding costs and higher power costs for replacing content in the caches. These power costs can be balanced out with lower power costs for content transport, however, probably only the most popular content will gain power from distributed schemes. For example, our preliminary work in Figure 3 indicates that a cache server only makes sense from an energy-perspective during the peak hours in the evening, when the content demand is high.

Research group

This project is planned for 4 years, starting on January 1, 2016. In case of approval and support from the Swedish Research Council (VR), we will recruit a PhD student to work in the project. The project will be performed within the Linneaus research environment Lund Center for Control of Complex Engineering Systems (LCCC), where the main applicant is one of the PIs and the group leader of the Feedback Computing Research area. Also, the research environment will include researchers at Acreo and SICS Swedish ICT as part of the main applicant's research projects on media distribution.

This project focuses on highly complex and cross-disciplinary topics, since it relates to areas usually not belonging to the same research community. For example, most work on power efficient data centers belongs to the research community of autonomic computing, whereas the work on energy-efficient networks is most often published in the networking community. The strength of our research group is that we work in all the related communities, and therefore, we have the unique cross-disciplinary comptence required for this project.

	Name	Current pos.	Main competences	Fund level
Main appl	Maria Kihl	Professor	Internet systems, performance models	20%
Other	N.N.	PhD student	Power consumption in content distribution architectures	80%
LCCC	Dr. Martina Maggio	Assistant Professor	Feedback computing, Power consumption in data centers	
LCCC	Prof. Karl Erik Arzen	Professor	Cyber-physical systems	
LCCC	William Tärneberg	PhD student	Performance modelling of telco clouds	
Acreo	Manxing Du	Researcher	Content demand patterns and traffic measurements	
SICS	Dr. Henrik Abrahamsson	Researcher	Cache architectures and content demand	

Significance

The proposed research project targets a crucial topic with both high academic and industrial importance and interests, namely the sustainability of the future Internet architectures. The research partners in this project work in several research communities, covering both autonomic computing and networking, and in both national and international projects with related activities. For example, Dr. Martina Maggio has an on-going VR project with title ”Power and temperature control for large-scale computing infrastructures”, where we expect to gain synergy effects on how to model power consumption in data centers and cache systems. Also, we have a large network of academic and industry connections that will gain from the scientific contributions generated in this project. The fundamental research proposed in this project is very seldom performed in the industry sector, due to the companies' business strategies and product-oriented view, as can be seen in the related work that are all coming from academica. However, with the funding from VR, we can achieve a fundamental holistic understanding of the sustainability of Internet architectures and applications. Also, the project would facilitate initiatives like, for example, Greenpeace's Clean Energy Index [32], which already has changed major companies' sustainability strategies [33].

Further, the proposed research group has a large network of research collaboration, both national and international. The main applicant is a PI in LCCC and a member of the Excellence Center Linköping-Lund in Information Technology (ELLIIT). Also, she is one of the PIs in the VR framework project Cloud Control, in collaboration with Umeå University. Further, she is one of the main researchers in the Celtic-Plus project NOTTS, with academic and industry partners from Sweden, Finland, France, Spain and Poland. Also, she participates in the EIT-ICT labs project Network for Future Media Distribution (NFMD) that has a clear energy focus during 2015. All these research environments are well established and planned to continue, which means that the contributions from this project will have a high visibility in both national and international forums. Some of our other research contacts outside our research centers and projects will be:

- Prof. Tarek Abdelzaher, CS, University of Illinois at Urbana Champaign
- Dr. John Wilkes, Google Inc.
- Dr. Simon Tuffs, previously Netflix, now at Life360
- Anders Näsman, Ericsson Broadcast Services
- Dag Lundén, TeliaSonera
- Magnus Hazell, Arkena (former Qbrick)
- David Karlsson, previously at Qbrick and Millicom, now at SVT

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[8] J. Dilley, B. Maggs, J. Parikh, H. Prokop, R. Sitaraman, and B. Weihl, “Globally distributed content delivery,” *IEEE Internet Computing*, vol. 6, 2002.

[9] K. J. Ma, R. Barto, and S. Bhatia, “A survey of schemes for internet-based video delivery,” *Journal of Network and Computer Applications*, vol. 34, 2011.

[10] U. Mandal, P. Chowdhury, C. Lange, A. Gladisch, and B. Mukherjee, "Energy-efficient networking for content distribution over telecom network infrastructure," *Optical Switching and Networking*, vol. 10, no. 4, 2013.
[11] J. Baliga, R. Ayre, K. Hinton, and R. Tucker, "Architectures for energy-efficient iptv networks," in *Conference on Optical Fiber Communication (OFC)*, 2009.
[12] C. Jayasundara, A. Nirmalathas, E. Wong, and C. A. Chan, "Energy efficient content distribution for VoD services," in *Optical Fiber Communication Conference and Exposition (OFC)*, 2011.
[13] C. Ge, Z. Sun, and N. Wang, "A survey of power-saving techniques on data centers and content delivery networks," *Communications Surveys Tutorials, IEEE*, vol. 15, no. 3, 2013.
[14] J. Baliga, K. Hinton, and R. Tucker, "Energy consumption of the internet," in *Conference on Optical Internet (COIN)*, 2007.
[15] J. Baliga, R. Ayre, W. Sorin, K. Hinton, and R. Tucker, "Energy consumption in access networks," in *Conference on Optical Fiber communication (OFC)*, 2008.
[16] U. Mandal, C. Lange, A. Gladisch, P. Chowdhury, and B. Mukherjee, "Energy-efficient content distribution over telecom network infrastructure," in *13th International Conference on Transparent Optical Networks (ICTON)*, 2011.
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[18] U. Mandal, C. Lange, A. Gladisch, and B. Mukherjee, "Should ISPs adopt hybrid CDN-P2P in IP-over-WDM networks: An energy-efficiency perspective," in *IEEE International Conference on Advanced Networks and Telecommuncations Systems (ANTS)*, 2012.
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[23] Z. Hasan, H. Boostanimehr, and V. Bhargava, "Green cellular networks: A survey, some research issues and challenges," *IEEE Communications Surveys & Tutorials*, vol. 13.
[24] L. Mattsson, "Energy-efficiency in computer networks - a meta-analysis," Bachelor thesis, Dept. of Electrical and Information Technology, Lund University, 2015.
[25] J. Grau, "Energy-efficient media content storage and distribution," Master thesis, Dept. of Electrical and Information Technology, Lund University, 2013.
[26] H. Abrahamsson and M. Nordmark, "Program popularity and viewer behaviour in a large TV-on-demand system," in *ACM Internet Measurement Conference*, 2012.
[27] L. Keys, S. Rivoire, and J. Davis, "The search for energy-efficient building blocks for the data center," *Lecture Notes in Computer Science*, vol. 6161, 2012.
[28] A. Vishwanath, K. Hinton, R. Ayre, and R. Tucker, "Modeling energy consumption in high-capacity routers and switches," *IEEE Journal on Selected Areas in Communication*, vol. 32, 2104.
[29] O. Arnold, F. Richter, G. Fettweis, and O. Blume, "Power consumption modeling of different base station types in heterogeneous cellular networks," in *Future Network and Mobile Summit*, 2010.
[30] L. Decreusefond, T. Vu, and P. Martins, "Modeling energy consumption in cellular networks," in *25th International Teletraffic Congress (ITC)*, 2013.
[31] Modelica and the Modelica Association, http://www.modelica.org/.
[32] "How dirty is your data – a look at the energy choices that power cloud computing," Greenpeace International, 2011.
[33] Bloomberg, "Apple data center will be totally green by 2013," http://www.bloomberg.com/news/articles/2012-05-17/apple-data-center-will-be-totally-green-by-2013, 2012.

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

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Budget and research resources

Project staff

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

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

Dedicated time for this project

	Role in the project	Name	Percent of full time
1	Applicant	Maria Kihl	20
2	Participating researcher	New PhD student	80

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	2019	Total
1	Applicant	Maria Kihl	20	216,000	220,000	225,000	229,000	890,000
2	Participating researcher	New PhD student	80	388,000	396,000	405,000	412,000	1,601,000
	Total			604,000	616,000	630,000	641,000	2,491,000

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

Running Costs

	Running Cost	Description	2016	2017	2018	2019	Total
1	Resor		50,000	50,000	50,000	50,000	200,000
	Total		50,000	50,000	50,000	50,000	200,000

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	604,000	616,000	630,000	641,000	2,491,000		2,491,000
Running costs	50,000	50,000	50,000	50,000	200,000		200,000
Depreciation costs					0		0
Premises					0		0
Subtotal	654,000	666,000	680,000	691,000	2,691,000	0	2,691,000
Indirect costs	262,000	266,000	272,000	276,000	1,076,000		1,076,000
Total project cost	916,000	932,000	952,000	967,000	3,767,000	0	3,767,000

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

The project grant will be used to partly fund Prof. Maria Kihl and a new PhD student including some travel expenses. Also, several other researchers will be involved in the project as described in the research plan. These researchers are fully funded by other projects.

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

CV for Maria Kihl

University Degree

MSc in Computer Science and Engineering, Lund University, 1993

Doctoral Degree

PhD in Communication Systems, Lund University, Mar 1999. Title of thesis: "Overload control strategies for Distributed communication networks". Supervisor: Prof. Ulf Körner

Qualification as Associate Professor

"Docent" in Communication Systems, Lund University, 2004

Current position

Professor in Internetworked Systems at Dept. of Electrical and Information Technology, Lund University from November 2014.

Previous positions

- Associate Professor at the Dept. of Electrical and Information Technology, Lund University, 2003 – 2014.
- Part time (25%) project manager for "Women in Engineering", Lund University, 2003-2004.
- Part time External Consultant at Malaysia Multimedia University, 2002-2003.
- Postdoctoral fellow, Department of Communication Systems, Lund University, 1999-2003.
- Ph.D. student and teaching assistant, Department of Communication Systems, 1994-1999.

International experience

- May 2005 – July 2006: Visiting Scholar at the Department of Electrical and Computer Engineering, North Carolina State University, USA.
- November 1995 – June 1996: Researcher at Software Engineering Research Center, Melbourne, Australia.

PhD Student Supervision

- William Tärneberg (main supervisor), Thesis subject: "Performance optimization and control of cloud systems", Planned PhD in 2018 (started September 2013).
- Manfred Dellkrantz (assistant supervisor), Thesis subject: "Modeling and control of server systems", planned PhD in 2017 (started June 2012).
- Jens A. Andersson (main supervisor), Thesis subject: "Network design and monitoring", planned Licentiate thesis in 2015.
- Payam Amani (main supervisor), Thesis subject: "Monitoring and Control of Telecommunication systems", planned licentiate thesis in 2015.
- Inigo Sedano (external supervisor), Thesis subject "Video over IP quality estimation", guest PhD student from Tecnalia, Spain, 2010-2011 (planned PhD in 2017).
- Martin A. Kjaer (assistant supervisor), Thesis title: "Disturbance rejection and control in web servers", PhD in 2009
- Mikael Andersson (main supervisor), Thesis title: "Overload control and performance of web servers", PhD dissertation in 2007.
- Jens K. Andersson (assistant supervisor), Thesis title: "Overload control and performance evaluation in a Parlay/OSA environment", PhD in 2007.
- Niklas Widell (assistant supervisor), Thesis title: Active resource management in middleware and service-oriented architectures", PhD in 2005.

Research grants

- NFMD (Network for Future Media Distribution), EIT-ICT labs project, grant holder and LU project manager, 2014-2015.
- "Cloud Control" funded by the Swedish Research Council (VR), 2013 – 2016, principal investigator.
- NOTTS (Next-generation over-the-top services), EUREKA/CelticPlus project, grant holder and LU project manager, 2013-2015.
- EFRAIM (Eco-system for future media distribution) funded by Vinnova, 2012-2014, principal investigator.
- IPNQSIS (IP Network Monitoring for Quality of Service Intelligent Support), EUREKA/CELTIC project, grant holder and LU project manager, 2011-2013.
- "Resource Allocation and Control of Distributed Service Management Systems" funded by the Swedish Research Council, 2010-2013, co-applicant.
- R2D2 (Road to media-aware user-dependent self-adaptive networks), EUREKA/CELTIC project, LU project manager, 2010-2012.
- TRAMMS (Traffic Measurements and Models in Multi-Service networks), EUREKA/CELTIC project, LU project manage, 2007-2010.
- The Swedish Research Council (VR) – Linneaus Center: "Lund Center for Control of Complex Systems – LCCC", 2008 – 2017 (one out of 10 PIs)
- "E-service stability and design of IP access networks" funded by Vinnova (Swedish Agency for Innovation), main grant holder, 2007-2011.
- "Modelling and control of server systems" funded by the Swedish Research Council, 2007-2009.

Other achievements

- Vice coordinator for the Lund Center for Control of Complex Engineering Systems (LCCC).
- PhD opponent for
  - Maté Csorba (Norwegian Univeristy of Science and Tecnhology) Thesis title: "Service design with performance and cost efficient deployment", 2011.
- Member of the PhD Committees for
  - Henrik Abrahamsson (Mälardalen University), Thesis title: "Network overload avoidance by traffic engineering and content caching", 2012.
  - Felipe Mata (Universidad Autonòma de Madrid, Spain), Thesis title: "Quality of service analysis of Internet links with minimal information", 2012.
  - Edison Pignaton De Freitas (Halmstad University), Thesis title: "Cooperative Context Aware Setup and Performance of Surveillance Missions Using Static and Mobile Wireless Sensor Networks", 2011.
  - Wolfgang John (Chalmers University, Sweden), Thesis title: "Characterization and classification of Internet backbone traffic", 2010.
  - Saowaphak Sasanus (University of Pittsburgh, USA), Thesis title: "Adaptive Multi-class Signaling Overload Control for Cellular Networks", 2008.
  - Andreas Johnsson (Mälardalen University, Sweden), Thesis title: "Modeling, implementation and evaluation of IP bandwidth measurements methods", 2007.
- Licentiate opponent for
  - Pehr Söderman (Royal Institute of Technology), Thesis title: "Tools and strategies for Experimental Development and Evaluation of Protocols", 2013.
  - Junaid Shaikh (Blekinge University), Thesis title: "Non-intrusive network-based estimation of web quality of experience indicators", 2012.
  - Johan Eklund (Karlstad University), Thesis title; "On switchover performance in multi-homed SCTP", 2010.
  - Katrin Sjöberg (Halmstad University), Thesis title: "Predictable and scalable medium access control in vehicular ad-hoc networks", 2009.

Publication list

Maria Kihl's Publications 2007–2015

All citation numbers are given according to **Google Scholar** in March,2015.
h-index 19; total number of citations: 1237

An updated publication list can be found on http://www.eit.lth.se/staff/maria.kihl

The five **all-time** most cited publications are:

- M.L. Sichitiu, M. Kihl, "Inter-Vehicle Communication Systems: A Survey", IEEE Communication Surveys & Tutorials, 2008. Number of citations: 270
- J. Cao, M. Andersson, C. Nyberg, and M. Kihl, "Web Server Performance Modeling using an M/G/1/K*PS Queue", 10th international conference on telecommunications, 2003. Number of citations: 121
- M. Kihl, M. Sichitiu, T. Ekeroth, and M. Rozenberg, "Reliable geographical multicast routing in vehicular ad-hoc networks", 5th International Conference on Wired/Wireless Internet Communications, 2007. Number of citations: 59
- A. Robertsson, B. Wittenmark, and M. Kihl, "Analysis and design of admission control in web-server systems", American Control Conference, 2003. Number of citations: 44
- A. Robertsson, B. Wittenmark, M. Kihl, and M. Andersson, "Design and evaluation of load control in web server system", American Control Conference, 2004. Number of citations: 44

1. Peer-Reviewed Journal Articles

References

[1] I. Sedano, K. Brunnström, M. Kihl, and A. Aurelius, "Full-reference video quality metric assisted the development of no-reference bitstream video quality metrics for real-time network monitoring", EURASIP Journal on Image and Video Processing, Vol. 2014, No. 4, 2014. Number of citations: 2

[2] P. Amani, B. Aspernäs, K. J. Åström, M. Dellkrantz, M. Kihl, G. Radu, A. Robertsson, and A. Torstensson, "Application of Control Theory to a Commercial Mobile Service Support System", International Journal On Advances in Telecommunications, Vol. 5, No. 3&4, 2012.

[3] S. Li, T. Abdelzaher, S. Wang, M Kihl,and A. Robertsson, "Temperature Aware Power Allocation: An Optimization Framework and Case Studies", Sustainable Computing: Informatics and Systems, 2012. Number of citations: 6

[4] L. Zhong, M. Kihl, X. Wang, "Topological model and analysis of the P2P BitTorrent protocol", International Journal of System Control and Information Processing, Vol. 1, No.1, 2012. Number of citations: 8

[5] K. Bür, and M. Kihl, "Evaluation of selective broadcast algorithms for safety applications in vehicular ad hoc networks", International Journal of Vehicular Technology, Vol. 2011, No. 730895, pp. 1-13, 2011. Number of citations: 12

[6] M. A. Kjaer, M. Kihl, A. Robertsson, ”Resource allocation and disturbance rejection in web servers using SLAs and virtualized servers”, IEEE Transactions on Network and Service Management, Vol. 6, No. 4, 2009. Number of citations: 26

[7] M. Kihl, M. Sichitiu, and H.P. Joshi, ”Design and Evaluation of two Geocast protocols for Vehicular Ad-hoc Networks”, Journal of Internet Engineering, No 1, 2008. Number of citations: 35

[8] M. Sichitiu and M. Kihl, ”Inter-Vehicle Communication Systems: A Survey”, IEEE Communication Surveys & Tutorials, 2008. Number of citations: 270

[9] M. Kihl, A. Robertsson, M. Andersson, and B. Wittenmark, ”Control-Theoretic Analysis of Admission Control Mechanisms for Web Server Systems”, World Wide Web Journal, Vol. 11, No. 1, 2008. Number of citations: 35

2. Peer-Reviewed Papers at International Conferences

[10] A. Ali-Eldin, M. Kihl, J. Tordsson, E. Elmroth, ”Analysis and Characterization of a Video-on-Demand Service Workload”, Accepted to ACM Multimedia Systems Conference (MMSys), 2015.

[11] J. Krzywda, W. Tärneberg, P-O. Östberg, M. Kihl, and E. Elmroth, ”Telco Clouds: Modelling and Simulation”, Accepted to 5th International Conference on Cloud Computing and Services Science (CLOSER), 2015.

[12] W. Tärneberg, A. Mehta, J. Tordsson, M. Kihl and E. Elmroth, ”Resource Management Challenges for the Infinite Cloud”, Accepted to Feedback Computing, 2015.

[13] M. Dellkrantz, J. Dürango, A. Robertsson and M. Kihl, ”Model-Based Deadtime Compensation of Virtual Machine Startup Times”, Accepted to Feedback Computing, 2015.

[14] M. Du, M. Kihl, Å. Arvidsson, C. Lagerstedt, and A. Gavler, ”Analysis of Prefetching Schemes for TV-on-Demand Service”, Accepted to International Conference on Digital Telecommunications, 2015.

[15] K. Wang, A. Gavler, M. Du, C. Lagerstedt, and M. Kihl, ”Power consumption analysis of energy-aware FTTH networks”, Accepted to International Conference on Digital Telecommunications, 2015.

[16] J. A Andersson, S Höst, D.l Cederholm and M Kihl, ”Analytic Model for Cross-Layer Dependencies in VDSL2 access networks”, 22nd IEEE International Conference on Software, Telecommunications and Computer Networks, 2014.

[17] W. Tärneberg and M. Kihl, ”Workload displacement and mobility in an omnipresent cloud topology”, 22nd IEEE International Conference on Software, Telecommunications and Computer Networks, 2014.

[18] J. Li, J. Wu, G. Dan, Å. Arvidsson and M. Kihl, ”Performance Analysis of Local Caching Replacement Policies for Internet Video Streaming Services”, 22nd IEEE International Conference on Software, Telecommunications and Computer Networks, 2014.

[19] M. Kihl, R. Larsson, N. Unnervik, J. Haberkamm, Å. Arvidsson and A.Aurelius, ”Analysis of Facebook content demand patterns”, IEEE International Conference on Smart Communications in Network Technologies, 2014.

[20] J. Li, H. Wang, A. Aurelius, M. Du, Å. Arvidsson, and M. Kihl, ”YouTube Traffic Content Analysis in the Perspective of Clip Category and Duration”, Fourth International Conference on Network of the Future (NoF’13), 2013.

[21] V. Nordell, A. Aurelius, A. Gavler, Å. Arvidsson, and M. Kihl, ”Concurrency and locality of content demand”, First International Workshop on Quality Monitoring, 2013.

[22] M. Kihl, E. Elmroth, J. Tordsson, K. E. Årzen, and A. Robertsson, ”The Challenge of Cloud Control”, 8th International Workshop on Feedback Computing, 2013.

[23] Å. Arvidsson, M. Du, A. Aurelius, and M. Kihl, ”Analysis of User Demand Patterns and Locality for Youtube traffic”, 25th International Teletraffic Congress, 2013. Number of citations: 5

[24] M. Dellkrantz, M. Kihl, and A. Robertsson, ”Performance Modeling and Analysis of a Database Server with Write-Heavy Workload”, European Conference on Service-Oriented and Cloud Computing, 2012.

[25] M. Dellkrantz, M. Kihl, A. Robertsson, and K. J. Åström, ”Event-Based Response Time Estimation”, 7th International Workshop on Feedback Computing, 2012.

[26] A. Aurelius, Å. Arvidsson, P. Heegard, B. Villa, M. Kihl, and Y. Zhang: ”How much of the bandwidth do we really use? An investigation of residential access traffic load”, 14th International Conference on Transparent Optical Networks, 2012.

[27] A. Ali-Eldin, M. Kihl, J. Tordsson, E. Elmroth, ”Efficient provision of bursty scientific workload on the cloud using adaptive elasticity control”, ACM Workshop on Scientific Cloud Computing, 2012. Number of citations: 26

[28] M. Kihl, P. Amani, A. Robertsson, G. Radu, M. Dellkrantz, and B. Aspernäs, ”Performance modelling of databases in a Telecommunication Service Management system”, International Conference on Digital Communications, 2012. Number of citations: 2

[29] M. Kihl, K. Bür, P. Mahanta, and E. Coelingh, ”Evaluation of LTE Downlink Scheduling Strategies in Vehicle-to-Infrastructure Communications for Traffic Safety Applications”, IEEE International Symposium on Computer Communications, 2012. Number of citations: 3

[30] I. Sedano, M. Kihl, K. Brunnström, and A. Aurelius, ”Reconstruction of incomplete decoded videos for use in objective quality metrics”, IEEE International Conference on Systems, Signals, and Image Processing, 2012.

[31] J. Li, A. Aurelius, V. Nordell, M. Du, Å. Arvidsson, and M. Kihl, ”A five year perspective of traffic pattern evolution in a residential broadband access network”, Future Network & Mobile Summit, 2012. Number of citations: 3

[32] I. Sedano, M. Kihl, K. Brunnström, A. Aurelius, ”Evaluation of video quality metrics on transmission distortions in H.264 coded videos”, IEEE International Symposium on Broadband Multimedia Systems and Broadcasting, 2011. Number of citations: 7

[33] A. Aurelius, C. Lagerstedt, and M. Kihl, ” Streaming media over the Internet: Flow based analysis in live access networks”, IEEE International Symposium on Broadband Multimedia Systems and Broadcasting, 2011. Number of citations: 8

[34] M. Kihl, G. Cedersjö, A. Robertsson, and B. Aspernäs, ”Performance measurements and modeling of database servers”, Sixth International Workshop on Feedback Control Implementation and Design in Computing Systems and Networks, 2011. Number of citations: 6

[35] P. Amani, M. Kihl, and A. Robertsson, ”Multi-step ahead response time prediction for single server queuing systems”, The 16th IEEE Symposium on Computers and Communications, 2011. Number of citations: 6

[36] A. Aurelius, Å. Arvidsson, M. Johansson, M. Kihl, and C. Lagerstedt, ”Leveraging network and traffic measurements for content distribution and interpersonal communication services with sufficient quality”, 13th International Conference on Transparent Optical Networks, 2011.

[37] P. Amani, M. Kihl, and A. Robertsson, ”NARX-based multi-step ahead response time prediction for database servers”, 11th International Conference on Intelligent Systems Design and Applications, 2011.

[38] M. Kihl, K. Bür, F. Tufvesson, and J.L. Aparicio Ojea, ”Simulation modelling and analysis of a realistic radio channel model for V2V communications”, IEEE International Workshop on Advanced Sensing, Networking and Control, 2010. Number of citations: 3

[39] M. Kihl, A. Aurelius, C. Lagerstedt, and P. Ödling, ”Traffic analysis and characterization of Internet user behavior”, International Congress on Ultra Modern Telecommunications and Control Systems, 2010. Number of citations: 25

[40] M. Kihl, A. Aurelius, and C. Lagerstedt, ”Analysis of World of Warcraft traffic patterns and user behavior”, International Congress on Ultra Modern Telecommunications and Control Systems, 2010. Number of citations: 11

[41] A. Aurelius, C. Lagerstedt, I. Sedano, S. Molnar, M. Kihl, and F. Mata, ”TRAMMS: Monitoring the evolution of residential broadband Internet traffic”, Future Network & Mobile Summit, 2010. Number of citations: 6

[42] G. Yu, T. Westholm, M. Kihl, I. Sedano, A. Aurelius, C. Lagerstedt, and P. Ödling, ”Analysis and characterization of IPTV user behavior”, IEEE Symposium on Broadband Multimedia Systems and Broadcasting, 2009. Number of citations: 21

[43] M. A. Kjaer, M. Kihl, and A. Robertsson, ”Response-Time Control of a Processor-Sharing System Using Virtualized Server Environments”, 17th IFAC World Congress, 2008.

[44] M. A. Kjaer, M. Kihl, and A. Robertsson, ”Response-Time Control of a Single Server Queue”, 46th IEEE Conference on Decision and Control, 2007. Number of citations: 6

[45] H. P. Joshi, M. Sichitiu, and M. Kihl, ”Distributed robust geocast: Multicast routing for inter-vehicle communication”, 1st Workshop on WiMax, Wireless and Mobility (in conjunction with 5th International Conference on Wired/Wireless Internet Communications), 2007. Number of citations: 40

[46] M. Kihl, M. Sichitiu, T. Ekeroth, and M. Rozenberg, ”Reliable geographical multicast routing in vehicular ad-hoc networks”, 5th International Conference on Wired/Wireless Internet Communications, 2007. Number of citations: 59

[47] L. Yan, M. Kihl, Y. Liu, and L. He, ”The Application of Inter-vehicle Communication System to ITS”, Geographic Information Science Research UK Conference, 2007.

3. Books and book chapters

[48] , M. Kihl and J.A. Andersson, ”Datakommunikation och Nätverk”, Studentlitteratur, 2013 (in Swedish).

[49] M. Kihl and J.A. Andersson, ”INTERNET”, Studentlitteratur, 2008 (in Swedish).

[50] M. Kihl and M. Sichitiu, ”VANETs: Performance issues”, Algorithms and Protocols for Wireless, Mobile Ad Hoc and Sensor Networks, Wiley & Sons, 2007.

[51] M. Kihl, ”Vehicular Network Applications and Services”, Vehicular Networks: Techniques, Standards, and Applications, CRC Press, 2009. Number of citations: 7

CV

Name: Maria Kihl	**Doctorial degree:** 1999-03-05
Birthdate: 19690127	**Academic title:** Professor
Gender: Female	**Employer:** No current employer

Research education

Dissertation title (swe)
Overload control strategies for distributed communication networks

Dissertation title (en)
Overload control strategies for distributed communication networks

Organisation	Unit	Supervisor
Lunds universitet, Sweden Sweden - Higher education Institutes	Elektro- och informationsteknik 107201	Ulf Körner

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
20204. Telekommunikation	ISSN 1101-3931	1999-03-05

Publications

Name: Maria Kihl	**Doctorial degree:** 1999-03-05
Birthdate: 19690127	**Academic title:** Professor
Gender: Female	**Employer:** No current employer

Kihl, Maria 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.