VETENSKAPSRÅDET
THE SWEDISH RESEARCH COUNCIL

Kansliets noteringar Kod	Dnr
2014-40425-116670-27	2014-4829

2014
Project Grant Junior Researchers

Area of science
Natural and Engineering Sciences
Announced grants
Research grants NT April 9, 2014
Total amount for which applied (kSEK)

2015	2016	2017	2018	2019
1054	1045	1112	1113	1197

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ADMINISTRATING ORGANISATION

Administrating Organisation
Chalmers tekniska högskola

DESCRIPTIVE DATA

Project title, Swedish (max 200 char)
ChaosNet: Distributed Computing for Low-Power Wireless Networks

Project title, English (max 200 char)
ChaosNet: Distributed Computing for Low-Power Wireless Networks

Abstract (max 1500 char)

Distributed Computing in low-power wireless networks such as Cyber-Physical Systems and the Internet of Thing poses unique challenges: Many applications in the automotive industry, health care, manufacturing and smart buildings are safety critical. They demand reliable distributed-computing at a message latency, energy efficiency, and scalability that today´s approaches cannot provide. In this project we will close this gap by taking a novel approach. We will base it on our recent advances in synchronous wireless transmissions and combine their efficiency with flexible in-network processing. The result will be a fast, reliable, and flexible approach to network-wide information sharing and distributed processing. We believe to achieve an improvement of more than two orders of magnitude over the state of the art.

Recently, we have evaluated the feasibility of our new approach in a simplified prototype implementation. Its initial publication received the best paper award at ACM SenSys 2013. Basing on this initial result, we will focus in this project on both the analytical and system aspects of our new approach. Our key goal will be to provide demanding primitives in distributed computing, such as reliable group communication and distributed consensus, and satisfy the performance requirements of safety-critical applications in Cyber-Physical Systems and the Internet of Things.

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Name of Applicant
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Abstract language
English

Keywords
Cyber-Physical Systems, Internet of Things, Distributed Computing, Low-Power Wireless Networking,

Review panel
NT-2, NT-14

Project also includes other research area

Classification codes (SCB) in order of priority
10201, 10202,

Aspects

Continuation grant
Application concerns: New grant
Registration Number:

Application is also submitted to

similar to: **identical to:**

ANIMAL STUDIES

Animal studies
No animal experiments

ENCLOSED APPENDICES

A, B, C, N, S

APPLIED FUNDING: THIS APPLICATION

Funding period (planned start and end date)
2015-01-01 -- 2019-12-31

Staff/ salaries (kSEK)

Main applicant	% of full time in the project	2015	2016	2017	2018	2019
Olaf Landsiedel	25	272	281	290	300	310
Other staff						
PhD Student	80	616	636	657	680	703
Total, salaries (kSEK):		888	917	947	980	1013

Other project related costs (kSEK)	2015	2016	2017	2018	2019
Other equipment (<SEK 20 thousand)	50	10	30	10	10
Conference and travel costs	55	55	55	55	55
Graduation Cost			15		50
Premesis	49	50	52	54	55
Direct IT costs	12	13	13	14	14
Total, other costs (kSEK):	166	128	165	133	184

Total amount for which applied (kSEK)

2015	2016	2017	2018	2019
1054	1045	1112	1113	1197

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Name of Applicant
Olaf, Landsiedel

Date of birth
790302-7956

ALL FUNDING

Other VR-projects (granted and applied) by the applicant and co-workers, if applic. (kSEK)

Funds received by the applicant from other funding sources, incl ALF-grant (kSEK)

POPULAR SCIENCE DESCRIPTION

Popularscience heading and description (max 4500 char)

Tillgång till internet och andra kommunikationskanaler är en viktig drivkraft i vårt moderna samhälle och de flesta av oss är redan uppkopplade. Nästa steg är att sätta uppkoppling och databehandling till fysiska föremål och platser: Även traditionellt "dumma" föremål som stegräknare, termostater och glödlampor njuter nu trådlös kommunikation. Förutsägelser tyder på att dessa smarta, anslutna föremål är snart flera än dagens traditionella anslutna enheter som smartphones eller datorer. År 2020 räknar vi med att nå 50 miljarder anslutna enheter. Dessa är så kallade cyberfysiska system och Internet of Things och de syftar till att göra vår vardag enklare, säkrare och bärkraftigare.

Cyberfysiska system och Internet of Things mäter och interagerar med den fysiska världen och ger nya möjligheter så som smarta elnät, intelligenta transportsystem och avancerad automatisering i fabriker och hem. De tillhandahåller säkerhets kritiska tjänster som behövs för vårt moderna samhälle, och deras tillgänglighet har signifikant betydelse, både för användare och för samhällsekonomin. Därmed medför de nya utmaningar mot de underliggande kommunikationssystemen och kräver: (1) tillförlitlig leverans av meddelanden, (2) realtidskrav på leverans av meddelanden i tidskritiska system, och (3) energieffektivitet som möjliggör att batteridrivna enheter ska fungera i många år. Inom detta projekt utvecklar vi nya kommunikationsprotokoll för att hantera dessa tre viktiga utmaningar.

Med våra nya nätverksprotokoll kommer vi att möjliggöra nya tillämpningar som bidrar till att göra vår vardag enklare, säkrare och bärkraftigare: Våra protokoll ska tillåta att autonoma fordon som bilar samarbetar på ett pålitligt sätt för att, till exempel, bestämma i vilken ordning de ska passera en korsning. På samma sätt kommer de att säkerställa tillförlitlig kommunikation för medicinska apparater såsom insulinpumpar eller pacemaker.

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Title of research programme
ChaosNet: Distributed Computing for Low-Power Wireless Networks

Appendix A

Research programme

ChaosNet: Distributed Computing for Low-Power Wireless Networks

1 Purpose and Aims

Our modern society increasingly depends on networked devices: Even traditionally "dumb" objects such as step counters, thermostats, and light bulbs begin to enjoy wireless communication. Such networked and cooperating objects are referred to as Cyber-Physical Systems (CPS) and Internet of Things (IoT). Predictions indicate that these will reach 50 billion devices by 2020 [1,2], see Fig. 1.

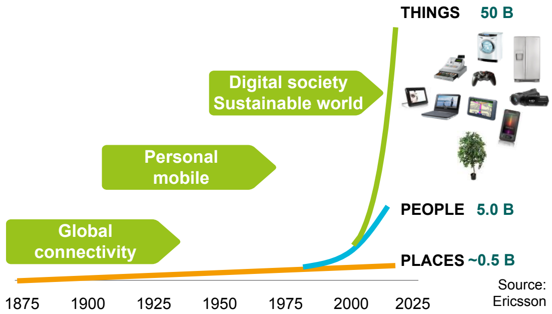


Figure 1: 50 billion connected devices.

Cyber-Physical Systems and the Internet of Things will spread into all aspects of our daily live, making it easier, safer, and more sustainable:

- *In smart buildings*, networked sensors will detect occupation of individual rooms and wirelessly manage lighting and HVAC to reduce our carbon footprint.
- *Ensuring our well-being*, wireless glucose-sensors will control insulin pumps to treat diabetes and interact with other body sensors to request medical support when needed.
- *On the road*, driverless cars will wirelessly cooperate on passing an intersection making our daily commute easier, safer, and greener.

CPS and IoT pose unique challenges when compared to traditional networking and distributed computing. Low data-rate communication, low cost, and battery operation have led to the development of new protocols tailored for wireless, low-power networking such as as ZigBee, WirelessHART, and Bluetooth LE. However, many application scenarios in the automotive industry, health care, manufacturing and smart buildings demand more than low power. We argue that once applications become safety critical, show real-time requirements, or include large dynamics such as mobility, they require reliable distributed computing at a message latency, energy efficiency, and scalability that today's approaches cannot provide.

The case for a new approach to distributed computing in low-power wireless networks: Despite large research efforts and significant progress, low-power wireless networking today is practically limited to applications *without* real-time or safety-critical requirements [3]. In this proposal, we argue that this is due the fundamental approach to wireless networking: Inspired by wired networks, such as the Internet, we typically consider the network as a discrete graph, design for point-to-point communication patterns such as client-server networking, assume that routes and links are stable, and use carrier sense or scheduling to ensure that transmissions do not collide. We argue that these make distributed computing in wireless networks challenging as they neglect key characteristics of low-power wireless networks: (1) Devices interact in large groups and not in pairs such as in client-server networks. (2) The network topology is highly dynamic due to mobility and dynamics of low-power wireless links [4], demanding more than discrete graphs and routing protocols assuming stable links. (3) The broadcast nature of the wireless medium and the high density of low-power networks result in transmissions being received by numerous neighboring nodes. Based on our recent advances on network-wide synchronous transmissions [5*][1] we will take a novel approach in this project. It will reflect the unique properties and demands of distributed computing in low-power wireless networks.

Our novel approach, ChaosNet, will be based on two new methods and their efficient interplay:

- *Nodes synchronously transmit* the data they want to share. Tight synchronization and physical layer phenomena such as capture [6] ensure that each neighboring node receives one of these transmissions with high probably despite packet collisions. Upon receiving, nodes process received and local

[1] Publications of the PI of this project are marked with *.

data and transmit the result synchronously themselves. This leads to a randomized, epidemic spreading of information in the network, motivating the name ChaosNet of this project. Though the capture effect is known since many decades, our novelty lies in exploiting it for fast, epidemic data spreading.
- *Distributed, in-network processing* between the receiving and re-sharing of data interconnects the epidemic data-flows in ChaosNet and allows us to employ application-specific processing such as merge and aggregation operations. These will be basis to realize demanding primitives in distributed computing, such as group communication or distributed consensus. Here, our novelty lies in the parallelism and interleaving of the data flows.

The result is a fast, reliable, and flexible approach to network-wide information sharing and distributed processing. Overall, it embraces wireless link and topology dynamics by dropping the need for routing, it exploits the broadcast nature of the wireless medium by addressing a packet to all neighboring nodes (and a fraction of them receives with high probability), and it drops traditional medium access-control by transmitting packets synchronously. The main goal of this project is to employ this novel approach to provide demanding primitives in distributed computing . These shall satisfy the performance requirements of safety-critical applications in low-power wireless networks.

Initial results: To evaluate the feasibility of this project we have recently developed a simplified version of our basic concept. Our initial results improve message latency and energy efficiency by about one order of magnitude over the state of the art. For example, we compute simple, network-wide aggregates, such as the maximum, in a 100-node wireless multi-hop network within less than 90 milliseconds. Its publication received the best paper award at ACM SenSys 2013 [5*].

Overall purpose: In this project we will take a novel approach on low-power wireless networking. *Our key goal is to provide demanding primitives in distributed computing, such as reliable group communication and distributed consensus, at a performance required by safety-critical applications in Cyber-Physical Systems and the Internet of Things.* Our approach, ChaosNet, will improve message latency, energy-efficiency, and scalabity of low-power networking by more than two orders of magnitude over the state of the art. In this project we will focus on both the analytical and system aspects of ChaosNet. More specifically, we will

1. explore the design space of our fundamental concept and develop new algorithms and models to guide analysis and performance optimization,
2. establish its system architecture and evolve it to provide protocol services, robustness, and security,
3. shape it to provide demanding primitives in distributed computing such as reliable group communication, distributed consensus, and advanced data aggregation.

2 Survey of the Field

We overview the state of the art of distributed computing in low-power wireless networks and its limitations in the context of safety-critical applications. We discuss (1) wireless link dynamics, (2) TDMA scheduling for deterministic networking, and (3) synchronous transmissions exploiting constructive interference.

Wireless link dynamics. Wireless links in Cyber-Physical Systems and the Internet of Things are highly dynamic [4]: nodes have cheap, low-power radios and apply duty-cycling to put them to sleep as much as possible. Their dynamics have led to new approaches to traditional distributed computing problems such as clock synchronization [7], graph coloring [8], or topology control [9]. For example, routing protocols [10,11*] rely on wireless-link estimation [12,13*] to measure link dynamics. Maintaining stable network topologies, they limit forwarding to neighboring nodes with links of consistently high quality. Newer protocols embrace wireless-link dynamics by temporarily utilizing unstable links for packet forwarding [14,15*] or adapting opportunistic routing [16*]. Overall, today's solutions provide latency, energy-efficiency, and reliability sufficient for most wireless *monitoring* applications [3]. However, these applications commonly have latency thresholds in the order of seconds. For applications with tight deadlines and strong real-time requirements these approaches cannot provide the required performance [17].

In this project we will depart from this traditional approach to wireless networking. We will close the gap between the requirements of safety-critical applications and the state of the art. It will achieve an improvement of more than two orders of magnitude in terms of key performance metrics such as message latency, and energy efficiency while providing the required reliability and scalability for safety-critical applications.

TDMA scheduling for deterministic networking. TDMA scheduling assigns time (and frequency) slots to each forwarder along the path of a packet [18,19*]. From an anlaytical perspective, this leads to deterministic, and often optimal, results. Thus, safety critical applications, such as closed-loop control with hard or firm real-time requirements, commonly depend on TDMA scheduling [20,21]. However, scheduling is inherently sensitive to wireless link dynamics and interference [22,23*]; and changes in traffic patterns or routes cause scheduling overhead [24]. In addition, the burstiness of wireless links [4,13*] commonly prohibits low latency bounds for delivery [25]. Due to this overhead, TDMA based deployments are commonly limited to a small scale [26].

This projects will provide the reliability and low-latency that safety-critical applications require without scalability and performance limitations of TDMA scheduling. We argue that its low jitter in message delivery will allow ChaosNet to provide deterministic performance. For example, our preliminary results indicate a coefficient of variation (CV) of less than 1 %.

Synchronous transmissions exploiting constructive interference. A new generation of approaches is based on on synchronous transmissions: The same packet is synchronously transmitted by multiple nodes. Tight synchronization ensures that these packets interfere constructively [27], i.e., their signals amplify each other instead of canceling out, and, thus, can be successfully received [28]. Typical applications are one-to-many communication patterns, such as network-wide flooding. In this setting they achieve severalfold improvements over the state of the art [29]. However, relying on constructive interference strongly limits the design space: Nodes must transmit the same packet and, as a result, applications are bound to one-to-many patterns. Moreover, the need for tight synchronization, 0.5 μs for IEEE 802.15.4 radios, limits their flexibility, e.g., to perform processing between receiving and transmitting a packet [30].

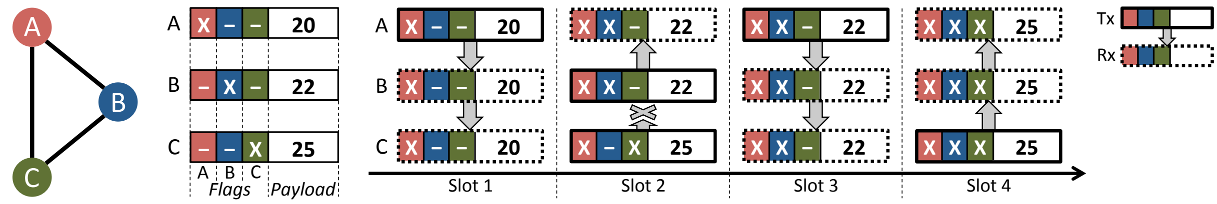
In this project, we will take a different approach to synchronous transmissions. It will allow each node to transmit its own, possibly different data and ease the tight synchronization requirements. As a result, our approach will significantly widen the application area and show strong performance improvements.

3 Project Description

In this section we discuss the basic idea of the project, outline work packages, and provide our time plan.

Basic Idea of ChaosNet At its core, we will base our approach on two main mechanisms:

- *Synchronous transmissions:* In ChaosNet, nodes synchronously send the, possibly different, data they want to share. Nodes overhearing these transmissions receive packets with high probability due to the *capture effect* [6]. Upon reception, nodes merge their own with the received data and transmit the resulting packets again synchronously. We argue that synchronous transmissions are key to the efficiency of our design.
- *In-network processing:* Nodes merge their own data with the received data according to a user-defined merge operator. ChaosNet allows users to freely program merge operators. Merge operators both enable and define the meaning of in-network data processing; we argue they are key to the versatility of our design.



(a) Nodes A, B, and C are in communication range of each other.

(b) All nodes prepare a packet with the proposed number and their own flag set.

(c) Node A initiates ChaosNet by sending its prepared packet in slot 1. B and C merge their own with A's data by taking the larger number and setting the bit of A. Both transmit synchronously in slot 2. A receives from B due to capture, merges data and manipulates the flags, and sends in slot 3. B does not send in slot 4 since it has nothing new to tell. ChaosNet completes in slot 4 when all nodes are aware of the maximum.

Figure 2: Basic operation of ChaosNet as three nodes try to find a consensus on the maximum number proposed. *A packet in ChaosNet consists of flags, one for every node bound to participate, and the payload, in this case the maximum number a node is aware of. During operation, the flags indicate which nodes already participated and the payload holds an intermediate (or the final) result.*

We illustrate these two mechanisms in a simple example: Each node proposes a number and the goal is to find a consensus among the nodes on the maximum number proposed, see Fig. 2. The operation of ChaosNet commences by letting an appointed node send its data. Over time more and more nodes join, ultimately covering the whole network. The process continues in a fully distributed manner until all nodes in the network share the same data. Data will spread in a random, epidemic fashion through the network, which motivated the name ChaosNet. ChaosNet will practically *parallelize* collection, processing, and dissemination of data *inside* the network. Overall, flexibly utilizing the merge operations and synchronous transmission strategies ChaosNet will create new opportunities for distributed computing in low-power wireless networks.

Project Overview In ChaosNet, our overall goal will be to develop distributed-computing primitives, such as reliable group communication and distributed consensus, for low-power wireless networks. They will provide the performance required by safety-critical applications in CPS and IoT and will improve message latency, energy-efficiency, and scalabity by two orders of magnitude over the state of the art. We will demonstrate these improvements in both simulation and experimental evaluation in large-scale testbeds containing hundreds of nodes.

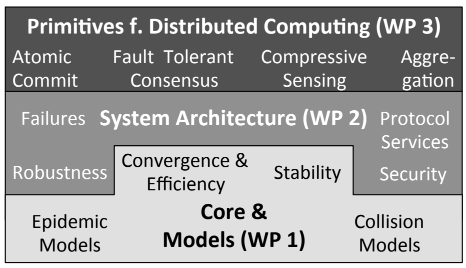


Figure 3: Project Overview.

The efficient combination of synchronous transmissions and in-network processing will form the underlying concept of ChaosNet and we have shown its feasibility in our preliminary results, see Sec. 5. Based on this concept, we will have three interconnected work packages to achieve our goals, see Fig. 3:

WP1. We will explore the design space of our fundamental concept and develop new algorithms and simulation models to guide analysis and performance optimization.

WP2. We will establish the system architecture of ChaosNet and evolve it to provide protocol services, robustness, and security.

WP3. We will shape ChaosNet to provide distributed-computing primitives such as reliable group communication, distributed consensus, and advanced data aggregation.

3.1 WP1: Explore the Design Space and Develop New Algorithms and Models

For our initial prototype the goal was to show the feasibility of our ideas on real-world testbeds. Thus, most design decisions were taken in an ad-hoc fashion without thorough analysis or deeply exploring the design space. Our goal in this WP is to (1) re-visit and analyze these to identify limitations of our original choices and to improve the overall performance, (2) to design new features and mechanisms beyond our initial prototype, (3) to build analytical and numerical models to support us in evaluating design choices. Overall, we address the following key design elements of ChaosNet:

WP1.1. Convergence and Efficiency. Information in ChaosNet spreads randomly in the network, a design inspired from epidemic routing [31]. However, in contrast to traditional epidemic routing, we have parallel, *interacting* flows, one per node in the network. While this parallelism and interaction is essential for the performance of ChaosNet, we need to extend the existing models for epidemic routing to include this. Utilizing these, we will develop and analyze forwarding policies depending on the rate of epidemic spreading, neighborhood density and wireless noise levels.

WP1.2. Stability of Synchronous Transmissions. The capture effect puts strong requirements on the synchronization of transmissions [30]. For example, without synchronization ChaosNet will not be able to exploit this effect and the probability of packet reception will drop significantly. We need to evaluate the stability of our mechanisms for time synchronization. A key goal is to determine bounds at which the system becomes unstable. Moreover, we will develop mechanisms to help nodes to detect a loss of synchronization and to efficiently re-synchronize.

WP1.3. Stability of the Forwarding Chain Reaction. In ChaosNet, nodes transmit a packet, synchronously with other nodes, whenever they receive a packet and learn new information. This leads to a form of chain reaction and timeouts help us to restart it in case it dies out prematurely. We need to evaluate and optimize the stability of this chain reaction. We have two key goals: (1) reduce timeouts to ensure high efficiency, (2) support a fast spreading of new information and suppress the spreading of information that nodes are already aware of.

WP1.4. Wireless Collision Models. In ChaosNet, the capture effect, when packets differ, and to a small degree constructive interference, for identical packets, form the underlying mechanisms for successful reception in presence of synchronous transmissions. We will develop models and perform experimental evaluation to deeply analyze how these two mechanisms interact and to determine the limitations of our approach: How many successful packet receptions are due to capture? How many are due to constructive interference? How does the synchronization quality impact these? How does density and the number of nearby synchronous transmissions impact the probability of successful receptions?

3.2 WP2: Establish our System Architecture: Robustness, Security, Protocol Services

To deploy demanding applications on ChaosNet, we need to develop the design principle of ChaosNet into a prototype system. As ChaosNet strongly differs in its underlying principles from the state art, we need to revisit many of today's approaches for low-power networking:

WP2.1. Failures: Nodes crashing, joining, and leaving. For dynamic scenarios including mobility or node crashes it is essential for ChaosNet to support join and leave operations at run-time. Node IDs, flags, initiators, wake-up schedules etc. need to be assigned dynamically and we need to achieve consensus among the participating nodes on these. In pre-studies, we have achieved promising, initial results by integrating the concept of virtual synchrony [32] into ChaosNet to ensure a consistent view of all nodes on, for example, node IDs.

WP2.2. Robustness: External interference such as IEEE 802.11 or Electronic Devices. External interference is a key challenge for any low-power wireless network. For example, pseudo-random channel hopping increases the robustness to such interference [22]. We will explore how to combine such approaches with the tight synchronization requirements of ChaosNet. While it is key for ChaosNet to enable safety-critical applications, channel hopping increases the possibility of synchronization loss and makes re-synchronization challenging.

WP2.3. Security: Encryption and Authentication. Safety-critical applications demand strong security, which we will deeply integrate into ChaosNet. While authentication and encryption are readily supported by today's low-power radios, synchronous transmissions in ChaosNet pose special challenges: We need to integrate them into the tight timing of receiving, processing, and transmitting. Furthermore, the fact that ChaosNet will allow each node to transit a possibly different packet enables us to assign unique keys to each node. This will ensure the security in case of theft or physical manipulation of individual nodes, such as key extraction.

WP2.4. Protocol Services: Targeting a wide range of applications, we need to tailor the services and interfaces that ChaosNet provides to allow applications to flexibly employ ChaosNet according to their requirements. Next to this, we need to create a narrow interface with limited complexity to ensure an efficient layering between the core system and applications deployed on top of it. We will follow an iterative approach to adapt interfaces and services when required, see Sec. 3.4,

3.3 WP3: Shape ChaosNet to provide Distributed-Computing Primitives

ChaosNet will provide a fast, network-wide broadcast combined with flexible, in-network processing. Practically, it provides nodes with a common view on data, similar to shared memory, with fast and reliable spreading of updates. This, combined with its ability to integrate processing before re-sharing updates, makes ChaosNet a powerful candidate for complex settings such as consensus or atomic commit. These are key primitives in distributed computing and we will realize and evaluate selected ones with ChaosNet in this WP. In this work package we will focus on:

WP3.1. Atomic commit: 2PC & 3PC. Two and three-phase commit are natural starting points. They are relatively simple approaches and we argue that by using multiple flags per node they can be readily realized in ChaosNet. Although their fault tolerance is limited, both mechanisms are widespread in distributed computing due to their light-weight design.

WP3.2. Fault Tolerant Consensus: Virtual Synchrony & Paxos. To provide fault tolerance, we will implement Virtual Synchrony [32] and Paxos [33]. For example, the concept of views makes Virtual Synchrony a perfect candidate for ChaosNet to agree on configurations such as node IDs etc. It allows nodes to determine whether their configuration is outdated due to network or node failures and then rejoin ChaosNet when required.

WP3.3. Distributed Processing: Aggregation & Compressive Sensing. Next to reliable group communication, ChaosNet requires distributed, in-network processing of data. For example, aggregation leads to significant bandwidth savings, allowing ChaosNet to reduce energy consumption and latency [34]. Similarly, compressive sensing has gained popularity in the research community to reduce bandwidth requirements [35]. We argue that the fast and reliable spreading of data in ChaosNet provides a powerful substrate to realize these.

3.4 Timetable and Organization

The project will last 5 years and be led by the applicant Olaf Landsiedel (PI). The PI and a PhD student under supervision of the PI will carry out the research. Weekly project meetings and internal workshops foster new ideas and provide the ground to discuss process and exchange feedback.

WP	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5
WP 1	✓		✓	✓	
WP 2		✓	✓		✓
WP 3	✓	✓	✓	✓	✓

Table 1: Project time plan.

WP1 and WP2 strongly depend on the applications requirements from WP3, see Table 1. Thus, WP 3 is scheduled for all years of the project. Our work on WP1 begins in the first year yielding to results for WP2 in the second year of the project. In the third year, we combine the results of all work packages leading to (a) an initial version of ChaosNet ready for deep evaluation and testing, (b) the detailed directions for years four and five. Following an iterative approach, the time plan in the final two years in similar to the plan in years one and two.

We will disseminate our results as follows: We will publish articles in leading journals and conferences. We will develop and maintain our implementation as open source software and will foster a community around it[2]. We will organize workshops and tutorials at top conferences, teach at summer schools[3], and scientific seminars at Chalmers.

4 Significance

Cyber-Physical Systems and the Internet of Things promise to make our daily life easier, safer, and more sustainable. However, once networked devices interact with physical processes they inherently face strong requirements in terms of message reliability, latency and often energy efficiency. We argue that despite significant research progress in the last decade, today's approaches to distributed computing in low-power wireless networks cannot provide such performance. As a result, low-power wireless networking today is practically limited to applications *without* real-time or safety-critical requirements [3]. In this project, we will develop a fundamentally new approach to close this gap. Our preliminary results underline the feasibility of our approach and indicate disruptive results.

We will cover both the analytical and system aspects of ChaosNet in this project: Will provide new methods, models, and tools to guide its design and analysis. Moreover, testbed-driven experimentation and practical system design will help us validate our results in real-world settings and applications. Overall, our project will give significant and novel contributions to the field for the following reasons:

- ChaosNet is the first approach that promises to close the gap between the networking and distributed computing requirements of wireless, safety-critical applications and the state of the art. No other approach is known that can provide this performance.
- Group communication and aggregation are essential building blocks in distributed computing. We consider realizing these at (a) a large scale and (b) practical performance as the “holy grail” of this project [36]. We argue that due to its fast and reliable network-wide broadcast and flexible in-network processing, our approach can realize this goal.
- Synchronous transmissions are mainly studied and implemented for the case of all nodes transmitting identical packets, see Sec. 2. However, we will show that synchronous transmissions of non identical packets leads to strong gains in flexibility and performance when combined efficiently with in-network processing.
- Nodes synchronously transmitting their own data, randomized packet reception based on capture, interconnected epidemic flows, and the chain of packet reception, process, transmission are the novel approaches in our method. Their individual aspects and their interplay open new research directions and we will develop new models, algorithms, and tools to guide their design.

5 Preliminary Results

To evaluate the feasibility of this project we have recently developed a simplified version of our new approach to low-power wireless networking. Preliminary results from both testbeds and simulations demonstrate that our pre-study scales efficiently to networks consisting of hundreds of nodes. It achieves improvements of about one order of magnitude over the state of the art in radio energy-efficiency and latency with almost 100 % reliability across all the scenarios we tested [5*]. For example, it computes simple aggregates, such as the maximum, in a 100-node wireless, multi-hop network within less than 90 milliseconds. Moreover, it provides a low jitter: In the above example, message latency has a coefficient of variation (CV) of less than 1 %. Overall, these results make our approach a promising candidate for safety-critical applications with strong real-time requirements. Our work in this new research direction received the best paper award at ACM Sensys 2013 and the best poster award ACM

[2] The implementation of our preliminary results is already available at https://github.com/olafland/chaos.

[3] The applicant is already invited to teach about the preliminary results at a summer school, see CV.

SenSys 2012 (see CV). Note that these preliminary results focus on the feasibility of the basic idea. This leaves a large body of open questions as discussed in Sec. 3.

In the field of distributed computing in low-power, wireless networks we were one the first groups to model and exploit the dynamics of wireless links: While it was an established method to limit communication to long-term stable links, we built models to predict their dynamics [13*] and integrated these into routing protocols to improve performance [15*]. Based on these insights the applicant continued to develop methods for opportunistic routing that are robust to wireless link dynamics [16*]. We have shown the optimality of our routing choices in dynamics environments [37*] and have integrated our results into the newly standardized RPL protocol [38*]. The applicant's further research in this field is listed in the attached publication record.

In summary, I believe that my preliminary results and my experience in the field provide a solid background for this project. My academic contributions and experience in developing methods and tools for efficient distributed computing in low-power wireless networks enable me to make significant contributions in the field and will ensure that the project successfully meets its goals.

6 Equipment

The department has compute resources for large-scale simulations and small testbeds, which we both utilize strongly throughout the project (see Sec. 7). To increase our capabilities for real-world evaluation and demonstration, we apply in this project for an extension of our stationary testbed (see Budget).

7 Need for Infrastructure

Evaluation of our results on large-scale testbeds is key to us to ensure real-world application scenarios and results. In Chalmers, we will use our local, stationary testbed (see Sec. 6) and our mobile testbed Gulliver (miniature-scale vehicles equipped for autonomous driving). Furthermore, Uppsala University has a testbed of mobile, networked robots, and both KTH and SICS have local stationary testbeds.

For large-scale evaluation and benchmarking, we rely on international infrastructures. We use testbeds at TU Berlin, ETH Zurich, National University of Singapore and other collaboration partners. Each testbed contains about 100 to 1000 devices in different settings, for example, one that covers a multi-floor office building. We have large experience in using these testbeds and our access is free of charge. Commonly, the testbeds allow for remote access, which reduces our travel costs. The testbeds are funded by the European Union or national governments to allow for real-world evaluation in CPS and IoT.

8 National and International Collaboration

Our key collaborator in this project will be Lothar Thiele's group at ETH Zurich. Since 2012 the applicant collaborates with two PhD students from his group, namely F. Ferrari and M. Zimmerling, on the research leading to this proposal, see Sec. 5 and Sec. 10. Led by the applicant, our two joint publications have received awards (see CV). Within this proposal we describe the research the applicant will conduct at Chalmers; the group at ETH has its own funding. Our research will be aligned and the groups will interact, including visits (see Budget). However, the projects will not explicitly overlap.

From applicant's department in Computer Science and Engineering, Philippas Tsigas, Marina Papatriantafilou, Elad Schiller will support this project on the analytical aspects of distributed computing such as epidemic routing, group communication, and self-stabilization. Further, we will collaborate with Katerina Mitrokotsa and Magnus Almgrem on ensuring security in ChaosNet. From the Signal and Systems department, the applicant collaborates with Henk Wymeersch and Erik Ström on communication, i.e., mainly base-band questions such as modulation and interference, and Maben Rabi on the automatic-control aspects in the project. In addition, our networks with the industry, in this project particularly

ABB, Ericsson, Volvo and some smaller SMEs focusing on low-power wireless, will help us to ensure realistic application scenarios and provide us with a platform to disseminate our results beyond publications.

In Sweden, the applicant maintains collaborations with Thiemo Voigt (SICS & Uppsala), Mikael Johansson, James Gross (both KTH), and Per Gunningberg (Uppsala) on low-power wireless networking [4]. These groups also have testbeds for the evaluation of ChaosNet, see Sec. 7. International collaborations in the project, next to ETH Zurich, include Utz Roedig (Lancaster University, UK), Silvia Santini, Ralf Steinmetz (both TU Darmstadt, Germany), Luca Mottola (Politecnico di Milano, Italy), and Philip Levis (Stanford University, California). Our international collaborations also provide us with access to a variety of testbeds which we use to evaluate our results in real-world settings (for example, TU Berlin, ETH Zurich, National University of Singapore, INRIA Grenoble, and INRIA Lille).

9 Other Grants

The applicant has founding from the Swedish Energy Agency and smaller funding from the European Union and Chalmers for ongoing research projects. These focus on related areas, but do not explicitly overlap with this project. Further applications, especially joint ones with the above collaboration partners, are planned on directions aligned to ChaosNet.

10 Independent Line of Research

The VR grant will make it possible for me to establish a new research direction in Chalmers: my own, independent group on distributed computing in low-power wireless networks. Note that neither the PhD nor PostDoc mentors of the applicant are directly involved in the project. Similarly, Lothar Thiele's role is limited to being the adviser of the two collaborating PhD students, he is not involved in this project itself.

11 Form of Employment

The applicant is employed as Assistant Professor (tenure track, tenure expected in 2015). In this proposal, we request funding to for a PhD student (80%) with supervision (25%) for 5 years.

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[4] We only list collaborations in the context of this project. Please see the publication list and CV for further collaborations.

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[14] T. Liu and A. Cerpa. "Foresee (4C): Wireless link Prediction using Link Features." In: *IPSN: Proc. of the ACM/IEEE Int. Conf. on Information Processing in Sensor Networks*. 2011.

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Kod

2014-40425-116670-27

Name of applicant

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Date of birth

790302-7956

Title of research programme

ChaosNet: Distributed Computing for Low-Power Wireless Networks

Appendix B

Curriculum vitae

Vetenskapsrådet, Box 1035, SE-101 38 Stockholm, tel. +46 (0)8 546 44 000, vetenskapsradet@vr.se

Curriculum Vitae

1. Higher Education Degrees

B.S. Equivalent 07/2002	Christian-Albrechts-University Kiel, Germany, Computer Science B.S. Equivalent (7/2002), Pre-Diploma (06/2001)
Master of Science 12/2003	University of Kansas, Computer Science (honors) Fulbright and Direct Exchange Scholarships

2. Doctoral Degree

PhD RWTH Aachen 03/2010	RWTH Aachen University, Germany, Computer Science, "Mechanisms, Models, and Tools for Flexible Protocol Development and Accurate Network Experimentation", Advisor: Klaus Wehrle

3. Postdoctoral Positions

PostDoc KTH / SICS 03/2010 – 01/2012	KTH Royal Institute of Technology, Electrical Engineering / Swedish Institute of Computer Science (SICS), Mentor: Prof. Mikael Johansson
Visiting Researcher Stanford, 02/2011	Stanford Information Networks Group (SING), Philip Levis, Stanford University

4. Qualification required for appointment as a docent

Expected 2015	All course and teaching requirements fulfilled

5. Present Position

Assistant Professor since 02/2012	Chalmers University of Technology, Department of Computer Science and Engineering, research (75%) and teaching (25%)

6. Previous Positions

7. Interruptions in Research

8. Supervision

Francisco Sant'anna (co-supervision)	Visiting PhD student, co-supervised with Philippas Tsigas, 2013 Selected outcome: Joint paper at ACM Sensys 2013
Hamed Khanmirza (co-supervision)	Visiting PhD student, co-supervised with Marina Papatriantafilou**,** 2012/2013
Master and Bachelor Theses	Supervision of more than 45 master and bachelor theses, see http://www.cse.chalmers.se/~olafl/thesis.php

9. Deductible time

10. Other

Best Paper Award ACM SenSys 2013	Olaf Landsiedel, Federico Ferrari, Marco Zimmerling, **Chaos: Versatile and Efficient All-to-All Data Sharing and In-Network Processing at Scale**, In *SenSys'13: Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems*, 2013.

Best Poster Award ACM SenSys 2012	Olaf Landsiedel, Federico Ferrari, Marco Zimmerling, **Poster Abstract: Capture Effect Based Communication Primitives**, In *SenSys'12: Proceedings of the 10th ACM Conference on Embedded Networked Sensor Systems*, 2012.
Academic Impact PhD in 2010	h-index: 11, i10-index: 13, total citation count: 656 (April 2014, based on Google Scholar)
Invited Talks	**Chaos: Tutorial and Hands-on,** Summer School "Cooperation of Robots and Sensor Networks for Emergency Response", TU Darmstadt, 2014 **Energy Efficiency and Energy Models**, 3rd Cloud-Control Workshop of the VR Cloud-Control Project, invited by Erik Elmroth, Umeå University, 2014 **Capture at Scale: Ultra-fast Wireless All-to-all Communication**, TU Darmstadt, invited by Silvia Santini and Ralf Steinmetz, 2013 **Towards Lightweight Logging and Replay of Embedded, Distributed Systems**, ASCoMS workshop, invited paper and talk, 2013 **Capture at Scale: Ultra-fast Wireless All-to-all Communication**, Swedish Institute of Computer Science (SICS), invited by Thiemo Voigt, 2013 **Low Power, Low Delay: Opportunistic Routing meets Duty Cycling,** Uppsala Univeristy, invited by Per Gunningberg, 2012 **Exploiting Link Dynamics**, Stanford, Stanford Information Networking Group (SING), Philip Levis, 2011 **Core: A P2P-based Connectionless Onion Router**, Dagstuhl Workshop on Peer-to-Peer Systems and Applications, 2006 **AEON: Accurate Prediction of Power Consumption in Sensor Nodes**, UCLA, Compilers Group, invited by Jens Palsberg, 2004
TPC Member	**2014:** IEEE PerCom 2014, IEEE DCOSS 2014, IEEE SenseApp, IEEE SOS-IOT 2014, ARCS 2014, SNCNW 2014, IEEE ISSNIP 2014, IEEE CCNC 2014 **2013:** IEEE DCOSS 2013, SNCNW 2013, ARCS 2013 **2012:** IEEE CPSCom 2012, SNCNW 2012, IEEE ICCNC 2012, ARCS 2012, **2011:** IEEE DCOSS 2011, IEEE CCNC 2011, OMNeT++ 2011 **2010 (and before):** IEEE DCOSS 2010, OMNeT++ 2009
Journal Reviews	ACM Transactions on Sensor Networks, IEEE Transactions on Mobile Computing, IEEE Transactions on Parallel and Distributed Systems, IEEE Sensors, IEEE Transactions on Computers, IEEE Transactions on Industrial Informatics
Local Support for Conference and Workshop Organization	**IEEE / ACM Cyber Physical Week 2010** (HSCC, ICCPS, IPSN, LCTES, and RTAS) in Stockholm, Sweden; **IEEE Peer-To-Peer 2008** in Aachen, Germany; **GI/ITG "Wireless Sensor Networks" 2007** in Aachen, Germany
Teaching Experience	Long-term teaching experience and strong course evaluation for my master–level course "Distributed Systems"
Leadership Training	Leadership training at Chalmers University of Technology for high potential Assistant Professors (total of 10 full days, 2012 / 2013)
Supervision & Pedagogics Training	PhD student supervision and pedagogics training as part of my qualification as Associate Professor, 2012 – 2014 (ongoing), 15 ECTS

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Title of research programme
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Appendix C

List of publications

Publication List (last 8 years)

Academic impact: h-index: 11, i10-index: 13, total citation count: 656 (Google Scholar)

The five most relevant publications for this project are marked with★; publications are available on www.cse.chalmers.se/~olafl/publications.php and on the applicant's profile on Google Scholar.

Note to reviewers not from computer science: Conference articles in computer science are peer-reviewed and considered as full publications. The top conferences in each subfield (like SenSys and IPSN below) typically have the highest impact factor within that field.

Five Most Cited Publications

a. Olaf Landsiedel, Klaus Wehrle, and Stefan Götz, **Accurate Prediction of Power Consumption in Sensor Networks**, In *Proc. of the 2nd IEEE Workshop on Embedded Networked Sensors (EmNetS-II)*, 2005, citations: 211

b. Muhammad Hamad Alizai, Olaf Landsiedel, Jo Agila Bitsch Link, Stefan Götz, and Klaus Wehrle, **Bursty Traffic over Bursty Links**, In *SenSys'09: Proc. of the 7th ACM Conference on Networked Embedded Sensor Systems*, 2009, citations: 70

c. Raimondas Sasnauskas, Olaf Landsiedel, Muhammad Hamad Alizai, Carsten Weise, Stefan Kowalewski, and Klaus Wehrle, **KleeNet: Discovering Insidious Interaction Bugs in Wireless Sensor Networks Before Deployment**, In *IPSN'10: Proc. of the 9th ACM/IEEE International Conference on Information Processing in Sensor Networks*, 2010, citations: 58

d. Olaf Landsiedel, Euhanna Ghadimi, Simon Duquennoy, and Mikael Johansson, **Low Power, Low Delay: Opportunistic Routing meets Duty Cycling**, In *IPSN'12: Proceedings of the 11th ACM/IEEE International Conference on Information Processing in Sensor Networks*, 2012, citations: 28

e. Alexander Becher, Olaf Landsiedel, Georg Kunz, and Klaus Wehrle, **Towards Short-Term Wireless Link Qualisty Estimation**, In *Proc. of Fifth ACM Workshop on Embedded Networked Sensors (Hot EmNets'08)*, 2008, citations: 27

I. Peer-Reviewed Articles

1. ★ Euhanna Ghadimi, Olaf Landsiedel, Pablo Soldati, Simon Duquennoy, Mikael Johansson, **Opportunistic Routing in Low Duty-Cycle Wireless Sensor Networks**, In *TOSN: ACM Transactions on Sensor Networks*, volume 10, issue 4, 2014, accepted, to be published
2. Thiemo Voigt, Utz Roedig, Olaf Landsiedel, Kasun Samarasinghe, Mahesh Bogadi Shankar Prasad, **On the Applicability of Network Coding in Wireless Sensor Networks**, In *ACM SIGBED Review - Special Issue on the 3rd International Workshop on Networks of Cooperating Objects*, volume 9, 2012, citations: 1
3. Navid Hassanzadeh, Olaf Landsiedel, Frederik Hermans, Olof Rensfelt, Thiemo Voigt, **Revisiting the Need for Mobile MAC Protocols in Wireless Sensor Networks**, In *ACM SIGBED Review - Special Issue on the 3rd International Workshop on Networks of Cooperating Objects*, volume 9, 2012, citations: -
4. Muhammad Hamad Alizai, Olaf Landsiedel, and Klaus Wehrle, **Exploiting the Burstiness of Intermediate Quality Wireless Links**, In *International Journal of Distributed Sensor Networks (IJDSN), 2012*, citations: 4
5. Muhammad Hamad Alizai, Olaf Landsiedel, and Klaus Wehrle, **Modeling Execution Time and Energy Consumption in Sensor Node Simulation**, In *PIK - Praxis der Informationsverarbeitung und Kommunikation, Special Issue on Energy Aware Systems*, 2009, citations: 3
6. Olaf Landsiedel, Tobias Heer, and Klaus Wehrle, **MHT: A Mobility-Aware Distributed Hash Table**, *Special Issue on Peer-to-Peer of the it - Information Technology Journal 49*, 2007, citations: 1

II. Peer-Reviewed Conference Contributions

7. Zhang Fu, Olaf Landsiedel, Magnus Almgren, Marina Papatriantafilou, **Managing your Trees: Insights from a Metropolitan-Scale Low-Power Wireless Network**, In *CCSES'14: Proceedings of the 3rd Workshop on Communications and Control for Smart Energy Systems held in conjunction with the 33rd IEEE International Conference on Computer Communications (INFOCOM)*, 2014, accepted, to be published
8. Francisco Sant Anna, Noemi Rodriguez, Roberto Ierusalimschy, Olaf Landsiedel, Philippas Tsigas, **Safe System-level Concurrency on Resource-Constrained Nodes**, In *SenSys'13: Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems*, 2013, citations: 3
9. ★ Olaf Landsiedel, Federico Ferrari, Marco Zimmerling, **Chaos: Versatile and Efficient All-to-All Data Sharing and In-Network Processing at Scale**, In *SenSys'13: Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems*, 2013, ***Best Paper Award***, citations: 1
10. ★ Simon Duquennoy, Olaf Landsiedel, Thiemo Voigt, **Let the Tree Bloom: Scalable Opportunistic Routing with ORPL**, In *SenSys'13: Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems*, 2013, citations: 1
11. Magnus Almgren, Daniel Cederman, Zhang Fu, Vincenzo Gulisano, Olaf Landsiedel, Marina Papatriantafilou, **Algorithms and Data Handling Towards Adaptive and Robust Electricity Networks**, In *Proceedings of the Chalmers Energy Conference*, 2013, Poster, citations: -
12. Christian Berger, Michel Chaudron, Rogardt Heldal, Olaf Landsiedel, Elad M. Schiller, **Model-based, Composable Simulation for the Development of Autonomous Miniature Vehicles**, In *Mod4Sim'13: 3rd International Workshop on Model-driven Approaches for Simulation Engineering at SCS/IEEE Symposium on Theory of Modeling and Simulation in conjunction with SpringSim*, 2013, citations: 5
13. Simon Duquennoy, Olaf Landsiedel, **Poster Abstract: Opportunistic RPL**, In *EWSN'13: Proceedings of the 10th European Conference on Wireless Sensor Networks*, 2013, Extended Abstract and Poster, citations: -
14. Olaf Landsiedel, Federico Ferrari, Marco Zimmerling, **Poster Abstract: Capture Effect Based Communication Primitives**, In *SenSys'12: Proceedings of the 10th ACM Conference on Embedded Networked Sensor Systems*, 2012, Extended Abstract and Poster, ***Best Poster Award***, citations: 1
15. Euhanna Ghadimi, Olaf Landsiedel, Pablo Soldati, and Mikael Johansson, **A Metric for Opportunistic Routing in Duty Cycled Wireless Sensor Networks**, In *SECON'12: Proceedings of the 9th IEEE Conference on Sensor, Mesh and Ad Hoc Communications and Networks*, 2012, citations: 5
16. Navid Hassanzadeh, Olaf Landsiedel, Frederik Hermans, Olof Rensfelt, and Thiemo Voigt, **Efficient Mobile Data Collection with Mobile Collect**, In *DCOSS'12: Proceedings of the 8th IEEE International Conference on Distributed Computing in Sensor Systems*, 2012, citations: 2
17. Antonio Gonga, Olaf Landsiedel, Pablo Soldati, and Mikael Johansson, **Revisiting Multi-Channel Communication to Mitigate Interference and Link Dynamics in Wireless Sensor Networks**, In *DCOSS'12: Proceedings of the 8th IEEE International Conference on Distributed Computing in Sensor Systems*, 2012, citations: 2
18. ★ Olaf Landsiedel, Euhanna Ghadimi, Simon Duquennoy, and Mikael Johansson, **Low Power, Low Delay: Opportunistic Routing meets Duty Cycling**, In *IPSN'12: Proceedings of the 11th ACM/IEEE International Conference on Information Processing in Sensor Networks*, 2012, citations: 28
19. Navid Hassanzadeh, Olaf Landsiedel, Frederik Hermans, Olof Rensfelt, and Thiemo Voigt, **Do Sensor Networks need Mobile MAC Protocols?**, In *CONET'12: Proceedings of the 3rd Workshop on Networks of Cooperating* Objects in conjunction with CPS Week, 2012, citations: -

20. Thiemo Voigt, Utz Roedig, Olaf Landsiedel, Kasun Samarasinghe, Mahesh Bogadi Shankar Prasad, **Practical Network Coding in Sensor Networks: Quo Vadis?**, In *CONET'12: Proceedings of the 3rd Workshop on Networks of Cooperating Objects* in conjunction with CPS Week, 2012, citations: 2
21. Antonio Gonga, Olaf Landsiedel, Pablo Soldati, and Mikael Johansson**, Poster Abstract: Multi-Channel Communication vs. Adaptive Routing for Reliable Communication in WSNs**, In *IPSN'12: Proceedings of the 11th ACM/IEEE International Conference on Information Processing in Sensor Networks*, 2012, Extended Abstract and Poster, citations: 1
22. Antonio Gonga, Olaf Landsiedel, and Mikael Johansson, **MobiSense: Power-Efficient Micro-Mobility in Wireless Sensor Networks**, In *DCOSS 2011: Proceedings of the 7th IEEE International Conference on Distributed Computing in Sensor Systems*, 2011, citations: 8
23. Jose Araujo, Euhanna Ghadimi, and Olaf Landsiedel, **Random-Access Medium Access Control in Wireless Sensor Networks: What's the best choice?**, In *ADHOC'11: Proceedings of the 10th Scandinavian Workshop on Wireless Ad-hoc Networks*, 2011, Extended Abstract and Poster, citations: -
24. Muhammad Hamad Alizai., Tobias Vaegs, Olaf Landsiedel, Stefan Götz, Jo Agila Bitsch Link, and Klaus Wehrle, **Probabilistic Addressing: Stable Addresses in Unstable Wireless Networks**, In *IPSN 2011: Proceedings of the 10th ACM/IEEE International Conference on Information Processing in Sensor Networks*, 2011, citations: 5
25. Olaf Landsiedel and Mikael Johansson, **Poster Abstract: Towards a Life without Link Estimation**, In *SenSys'10: Proc. of the 7th ACM Conference on Embedded Networked Sensor Systems*, 2010, Extended Abstract and Poster, citations: 4
26. Georg Kunz, Olaf Landsiedel, James Gross, Stefan Götz, Farshad Naghibi, and Klaus Wehrle, **Expanding the Event Horizon in Parallelized Network Simulations**, In *MASCOTS'10: Proc. of the 18th Annual Meeting of the IEEE/ACM International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems,* 2010, citations: 8
27. Waqaas Munawar, Muhammad Hamad Alizai, Olaf Landsiedel, and Klaus Wehrle, **Dynamic TinyOS: Modular and Transparent Incremental Code-Updates for Sensor Networks**, In *ICC'10: Proc. of the IEEE International Conference on Communications*, 2010, citations: 22
28. Raimondas Sasnauskas, Olaf Landsiedel, Muhammad Hamad Alizai, Carsten Weise, Stefan Kowalewski, and Klaus Wehrle, **KleeNet: Discovering Insidious Interaction Bugs in Wireless Sensor Networks Before Deployment**, In *IPSN'10: Proc. of the 9th ACM/IEEE International Conference on Information Processing in Sensor Networks*, 2010, citations: 58
29. Muhammad Hamad Alizai, Tobias Vaegs, Olaf Landsiedel, Raimondas Sasnauskas, and Klaus Wehrle, **Poster Abstract: Statistical Vector based Point-to-Point Routing in Wireless Networks**, In *IPSN'10: Proc. of the 9th ACM/IEEE International Conference on Information Processing in Sensor Networks*, 2010, Extended Abstract and Poster, citations: 2
30. Muhammad Hamad Alizai, Georg Kunz, Olaf Landsiedel, and Klaus Wehrle, **Promoting Power to a First Class Metric in Network Simulations**, *In Proc. of the Workshop on Energy Aware Systems, in conjunction with GI/ITG ARCS 2010*, 2010, citations: 3
31. ★ Muhammad Hamad Alizai, Olaf Landsiedel, Jo Agila Bitsch Link, Stefan Götz, and Klaus Wehrle, **Bursty Traffic over Bursty Links**, In *SenSys'09: Proc. of the 7th ACM Conference on Networked Embedded Sensor Systems*, 2009, citations: 70
32. Georg Kunz, Olaf Landsiedel, and Klaus Wehrle, **Horizon - Exploiting Timing Information for Parallel Network Simulation**, In *MASCOTS'09: Proc. of the 17th Annual Meeting of the IEEE International Symposium on Modelling, Analysis and Simulation of Computer and Telecommunication Systems,* 2009, citations: -
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III. Review articles

My review articles are published as book chapters. To avoid duplication, I do not list them here.

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V. Patents

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VI. Open Access Computer Programs

54. Olaf Landsiedel, Federico Ferrari, Marco Zimmerling, **Chaos: Versatile and Efficient All-to-All Data Sharing and In-Network Processing at Scale,** On *GitHub (github.com/olafland/chaos)*
55. Simon Duquennoy, Olaf Landsiedel, Thiemo Voigt, **Let the Tree Bloom: Scalable Opportunistic Routing with ORPL,** On *GitHub (github.com/simonduq/orpl)*
56. Francisco Sant'Anna et.al., **Céu: The Programming Language**, On *www.ceu-lang.org*
57. Olaf Landsiedel, **Opportunistic Routing in TinyOS**, On *GitHub (github.com/olafland/orw)*
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VII. Popular Science Articles and Presentations

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VETENSKAPSRÅDET
THE SWEDISH RESEARCH COUNCIL

Title of research programme

Kod
2014-40425-116670-27

Name of applicant
Olaf, Landsiedel

Date of birth
790302-7956

Appendix N

Budget and research resources

Vetenskapsrådet, Box 1035, SE-101 38 Stockholm, tel. +46 (0)8 546 44 000, vetenskapsradet@vr.se

1 Project Budget

1.1 Salaries

The proposal requests funding for a PhD student and supervision. The PhD student's research will be financed for 80%. The adviser's research shall be financed for 25%.

1.2 Publication and Travel Expenses

For the publication of results, e.g., publishing at conferences and workshops, we apply for 40 kSEK yearly. We assume two international events (16 kSEK, each), and one national event (8 kSEK). For visits to collaboration partners we plan 15 kSEK yearly.

1.3 Equipment

The department already has compute resources for large-scale simulations and a small wireless sensor network testbed. We will strongly utilize both throughout the project. To increase our capabilities of real-world evaluation and demonstration of results, we extend the testbed in this project. This is essential for our project, as we target large-scale applications. We request funding for 50 additional sensor nodes and testbed infrastructure (control server, cabling for remote debugging, etc.) for a total of 40 kSEK (20 kSEK in years 1 and 3, respectively). Additionally, we apply for laptop and screen for the PhD student (20 kSEK) and IT equipment (10 kSEK per year).

1.4 Other Costs

The project calculation outlines overhead and indirect costs. Overhead includes the cost for the use of Chalmers' premises and offices as well as the IT services and infrastructure. To cover graduation, i.e., thesis printing, travel costs of the opponents, etc., at licentiate and PhD defense, we apply for 15 kSEK and 50 kSEK respectively.

2 Total Research Resources of the Project

In this proposal we request funding for our group at Chalmers. Our collaboration partners, especially ETH Zurich, have their own funding. For this reason, this proposal describes the contributions of the applicant. The contributions of our collaborators are aligned and connected with ours but do not explicitly overlap. Additional applications are planned throughout 2014, in particular together with the collaboration partners.

Kod
2014-40425-116670-27

Name of applicant
Olaf, Landsiedel

Date of birth
790302-7956

Dnr
2014 -

Reg date
2014-04-09 23:38:00

VETENSKAPSRÅDET
THE SWEDISH RESEARCH COUNCIL

Project title
ChaosNet: Distributed Computing for Low-Power Wireless Networks

NT

NT-2, NT-14

Research grants NT April 9, 2014
Project Grant Junior Researchers
*Övrigt generellt
Chalmers tekniska högskola

Appendix S

Signatures

2015	2016	2017	2018	2019
1054	1045	1112	1113	1197

2015-01-01 -- 2019-12-31

Applicant

Date

Head of department at host University

Clarifi cation of signature

Telephone

A signature on the application is required not only from the applicant but also from the authorised representative of the administrating organisation/institution or equivalent (normally the head of the department or establishment where the research is to be conducted). The signature confirms that the department can accommodate the proposed research, position or equipment; that the costing in the application is approved for the department's part, that any proposed experimentation on human or animal subjects has been reported, and that the applicant has reported any secondary occupations and commercial ties (s)he may have, and nothing inconsistent with good research practice has thereby emerged. The applicant must have discussed these conditions with the representative of the administrating organisation/institution or equivalent before the latter approves and signs the application.

NOTE the exceptions!
Please note that a different procedure applies for the following types of grants:

- Infrastructure- Operation Grants
- Infrastructure- Grants for Expensive Equipment
- Infrastructure- Grants for Large Databases
- Framework Grant SIMSAM
- International Recruitment

For these types of grants the vice-chancellor, instead of the head of department, must sign Appendix S. Thereby (s)he confirms the commitments of the administrative organization. The details are specified in the Call for Proposals, published at www.vr.se.

Vetenskapsrådets noteringar
Kod

2014-40425-116670-27

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