GigaHertz Centre

Chalmers University of Technology
Industrial Research Institutes
Companies
Swedish Governmental Agency for Innovation Systems (Vinnova)

2017.01.01 – 2021.12.31

Operational plan

Organisation, activities, research programme and budget

GigaHertz Centre

A Competence Centre hosted by Chalmers University of Technology

www.chalmers.se/ghz

This report describes the planned activities for GigaHertz Centre year 2017-2021. The report was approved by the Board of ChaseOn-GHz Centre on 2017.02.02, approved by Vinnova 2017.03.10, updated 2017.03.24.p

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Executive Summary

The GigaHertz Centre (GHz Centre) is a joint research and innovation centre between Chalmers University of Technology and industrial partners. The mission of GHz Centre is to carry out collaborative research in selected high-frequency technologies and to bring the results from Chalmers to an industrial exploitation phase primarily through its company partners. GHz Centre is part of the Competence Centre program run organised by the Swedish Governmental Agency for Innovation Systems (Vinnova).

GHz Centre has been run four consecutive stages year 2007-2016. In the present document, the activities and budget for year 2017-2021 are described. Twelve companies and one research institute are participating: Ericsson, Gotmic, Infineon Technologies, Low Noise Factory, National Instruments, Omnisys Instruments, Qamcom Research and Technology, Ruag Space, Saab, Research Institutes of Sweden, United Monolithic Semiconductors and Wasa Millimeter Wave. Five of the company partners are SMEs, all of them spin-offs from Chalmers. At Chalmers, four laboratories at three departments will participate. Department of Microtechnology and Nanoscience at Chalmers acts as the host for GHz Centre.

The vision of GHz Centre is the new wireless hardware that radically increases data rate, sensing capability and energy efficiency than possible today in businesses critical to Swedish competitiveness. A research programme reflecting the long-term needs among the industrial partners is planned, divided into four projects: Efficient and Linear Millimeter Wave Transmitter, Smart Receivers for Future Linear RF Systems, Thermal effects, and Integrated THz Systems.

The overall goals of the research programme are to produce 8 success stories of industrial impact, 100 scientific publications in referred journals or international conferences of which at least 40 are co-authored between Chalmers and industrial partners, and 8 PhDs of which at least 5 are hired by relevant industry.

Pre-defined indicators are used to highlight progress in the projects and create incitements for inventions and publications from the researchers. Impact parameters capture the industrial uptake of the research into innovation and commercialisation at companies. The parties' rights and obligations to results emanating from the projects is regulated by a consortium agreement and individual agreements for the GHz Centre researchers at Chalmers.

Apart from the research activity defined here, the listing of goals and strategies shows that GHz Centre will be an active and visible player in the microwave community. Furthermore, we plan annual meetings, technical workshops, fostering leadership, and a recruitment campaign. An International Advisory Board consisting of outstanding experts will be recruited to give GHz Centre advice in its near and long-term development.

The total five-year budget is 135 MSEK (60 MSEK cash) of which industry finances 48% (39% cash), Chalmers 27% (3% cash), and Vinnova 26% (58% cash). Around 48 person-years are provided in kind for the GHz Centre projects by the partners.

Contents

1 Centre Objectives and Long-term Strategic Plan

GigaHertz Centre (GHz Centre) is a collaboration between Chalmers University of Technology (Chalmers), research institutes and company partners to carry out research and innovation in wireless communication and sensor technologies. All partners invest resources in the GHz Centre with the intent to carry out research projects according to a jointly agreed plan. The projects are selected from common technical needs decided by the industrial partners.

The GHz Centre is administered, hosted and lead by Chalmers. The GHz Centre is run under the framework of the Competence Centre programme initiated and organised by the Swedish Governmental Agency for Innovation Systems (Vinnova). The main objective for a Competence Centre is to run joint research and innovation projects between commercial and non-commercial actors. The long-term goal of the Competence Centre program is to promote sustainable growth effects in Sweden. So-called success criteria for Competence Centres as defined by Vinnova have been used as guide for the formulation of this research programme. The three most important criteria for success are:

- Promoting sustainable growth by ensuring that new knowledge and new technological developments generated lead to new products, processes and services.
- Leading international research in different fields in collaboration between the private and public sectors, universities and colleges, research institutes and other organisations which conduct research.
- Set up in innovation environments with effective innovation operations so that strong research and innovation milieus can be created.

1.1 *Vision*

Our vision is to create the new wireless hardware which radically increases data rate, sensing capability and energy efficiency than possible today for businesses critical to Swedish competitiveness.

1.2 *Mission*

Our mission is to bring scientific advances aimed for future wireless communication and sensors faster to industrial exploitation.

1.3 *Goals*

GHz Centre addresses the future generation of highly integrated wireless hardware for communication, defence and space system applications. The major overall technical goals are:

- New design and test methodologies to improve energy efficiency in millimetre wave MIMO transmitter systems
- Improve linearity vs. efficiency trade-offs in multi-antenna receiving systems
- Understand thermal and electrical effects on device level and their effects on multi antenna system level
- Progress in components for cryogenic microwave/mm-wave low noise amplifiers and room-temperature Schottky-based mixers up to 2 THz
- Measurement techniques with VNAs up to 1.5 THz

We define three major measurable goals for GHz Centre. These goals also serve as the key performance metrics of the centre.

Table I

Goal	Number	Comment	Definition
Impact	8	Case of industrial impact originating from the Centre	Stories formally approved by the Board
Scientific publications	100	At least 40% co-authored between Chalmers and industry	Refereed international journal or conference
Educated personnel	8	At least 5 hired by relevant industry	Examined PhDs from Chalmers

1.4 *Anticipated results*

The centre collaboration will mean that scientific output from GHz Centre will help to accelerate industrial exploitation in the following areas:

- Digitally intense millimetre-wave communication transmitter and receivers
- Wideband MIMO radar systems
- Guidelines and rules for thermal management in industrial high-frequency electronics

- A testbed for electro thermal characterization
- 1 THz radar transceiver
- 100+ GHz LNA module with state of the art low noise figure

We foresee industrial impact from the results in GHz Centre in:

- Helping telecom industry to accelerate 5G development in the mm-wave transceiver architecture using a co-design approach between analog, digital and signal processing and multi-antenna systems
- Highly integrated radar transceivers for defence/security
- Schottky-diode modules used in THz radiometers for space missions
- High-resolution radar transceiver for security applications
- Cryogenic low-noise amplifiers enabling higher sensitivity in astronomy receiver arrays and quantum computing read-out

1.5 *Overall strategy*

- Run four specific research projects gathering several companies and Chalmers researchers and students. In order to avoid project silos, the projects in the centre shall be adjacent and share some Chalmers staff, company partners, and research laboratories. Nonetheless each projects must be distinctly defined with unique objectives and technical goals.
- Build project teams with senior researchers, students and engineers from (1) university and industries (2) several disciplines in the value chain (components to systems to applications). This means multi-disciplinary research between academic groups and industry, from various branches, geographical regions and sizes including small- and medium enterprises (SMEs).
- Create efficient meeting places for the constellations above both for operational as well as strategic work: Projects, laboratories, steering board and stakeholder meetings. Have an agenda to meet across the projects at centre days, scientific workshops and seminars, in particular with the ChaseOn antenna system centre representing another part of the value chain not covered by the GHz Centre profile.
- International strategy: Have a global setting for the centre by partnering with companies complementing Swedish industry with respect to competences and resources. Recruit an international scientific advisory board, Moreover, the academic international exchange is taking place by postdocs, visits and sabbaticals to and from Chalmers' university collaborators.
- Stimulate the participation of SMEs by meeting their special demands in the projects to be launched in a special call from Vinnova.
- Couple the undergraduate education at Chalmers with the GHz Centre by engaging researchers in the projects involved in teaching at Chalmers. Involve industrial co-workers to supervise and give guest lectures at courses at Chalmers. Encourage industrial PhDs and adjunct professorships.

1.6 *Plan for evaluation in relation to goals*

Indicators

While the goals are measurable and will highlight key metrics of the GHz Centre, the plan for regular evaluation must depend upon indicators which show the progress in a more rapid manner compared to the traditional slow measures such as examined PhDs.

The following indicators will be used to monitor progress towards the goals and reported at each board meeting

- Manuscript and invention disclosures and the portion of these which are co-authored
- Mobility of people between Chalmers and industry
- M.Sc. theses
- Licentiate theses

Goals

The goals listed in Section 1.3 will be followed up annually at the time for annual reporting. Here a plan is presented on how to achieve the set goals.

Impact goal

The impact goal is what differs a competence centre from a traditional research excellence centre at the university. The GHz Center is based upon university-company collaborations and as a result, the focus is on *industrial* impact emanating from the centre. Industrial impact will in turn affect the society in terms of economical growth and more jobs. An impact goal also serves a purpose of changing the academic culture at the university toward a more entrepreneurial direction. Impact has larger meaning than pure transfer of results from university to industry; Ideas, research and innovation may take many routes between all actors in a competence centre.

We will use the following five parameters to define and measure centre impact originating from GHz Centre results:

1. **Mobility of people between Chalmers and industry**

- Industry people spending > 3 weeks at Chalmers.
- Chalmers people spending > 3 weeks at industry
- Chalmers PhD students and senior researchers hired by relevant industry

2. **Know-how (including intellectual property) between Chalmers and industry including involvement in undergraduate education**

- Manuscripts and inventions disclosed from Chalmers to *all* industrial partners long before being made public
- Co-published scientific papers Chalmers- industry
- Updated industrial roadmaps of new RF/microwave technologies made possible by GHz Centre results
- Patents and licenses
- Courses at Chalmers with GHz Centre staff enabling industrial participation

3. **Demonstrators, test beds, prototypes, methods, manufacturing and selling of new or improved products**

- GHz Centre results utilized in the industrial development for new products
- GHz Centre results which are commercialized

4. **New companies or industrial growth**

- Spin offs emanating from GHz Centre results
- GHz Centre results leading to industrial growth effects (such effects are normally only traceable for small companies, in particular recent spin offs)

5. **Industrial impact stories presenting concrete cases from industry and Chalmers**

- An impact story is published in the form of a public viewgraph presenting a concrete case of academic *and* industrial result materialised by GHz Centre collaboration. The story is approved by the Centre Board. All impact stories are published at http://www.chalmers.se/ghz/EN/success-stories This parameter is defined as a major goal of GHz Centre.

Year	Action	Documentation	Comment
2017	Formulate exploitation plans as an integral part of each project Call for SME projects according to Vinnovas planned call 2017 in competence centres. Prepare a questionnaire to GHz industry based upon the impact parameters to follow up the defined impact parameters Follow up the mobility and disclosure indicator wrt co-publishing	Project plans Board presentation and protocol Annual reporting to Vinnova	
2018	1st questionnaire to industrial partners. Report to Vinnova and board Reporting of SME projects	Results collected from the questionnaire Dedicated board meeting on how to follow up the impact goal	
2019	2nd questionnaire to industrial partners. Report to Vinnova and board Revision of exploitation plans. Reporting of SME projects Formulation of impact stories (if available)	Updated project plans wrt exploitation Mid-term evaluation of the impact goal. Board approval of impact	

2020	3rd questionnaire to industrial partners. Report to Vinnova and board Reporting of SME projects Formulation of impact stories (if available) Follow up the mobility and disclosure indicator wrt co-publishing	Board approval of impact	
2021	Follow-up of revised exploitation plans 4th questionnaire to industrial partners. Report to Vinnova and board Final reporting of SME projects Formulation of impact stories (if available)	Final evaluation of the impact goal and if it was achieved Board approval of impact Five-year report to Vinnova (Spring 2022)	End of 2021
2026	Follow up of long-term exploitation in industry. Formulation of long-term success stories		5 year after centre closure

Scientific publications

Scientific publications constitute the basic output for the research conducted in the centre. We aim to publish in the best scientific journals and international conferences in the field of wireless and sensing technologies.

This number is counted as a manuscript accepted for publication in an international scientific journal (e.g. IEEE T-MTT) or international conference with a quality-review system (e.g. IMS).

Year	Action	Documentation	Comment
2017	Every project sets up a dissemination plan an publication goals. Use the indicators to highlight quick progress. Agree a format how to report results such as invited talks, seminars, workshops, national symposia etc Publishing of research results from the GHz Centre at the best international conferences and journals in our community.	Disclosures of manuscripts Annual report to Vinnova Approval by board Web update	
2018	Pursue publishing according to the agreed format. Analysis of the co-author situation and the indicators used.	Documented in progress reports and annual reports. Publications are published on www.chalmers.se/ghz Reporting to board Annual report to Vinnova	

2019	Follow up the goal. Revision if needed Pursue publishing	Disclosures of manuscripts Reporting to board Annual report to Vinnova	
2020	Pursue publishing	Disclosures of manuscripts Reporting to board Annual report to Vinnova	
2021	Pursue publishing Bibliometric analysis Co-authorship Chalmers-industry reporting	Disclosures of manuscripts Reporting to board Annual report to Vinnova Five-year report to Vinnova (Spring 202	

PhDs

The number of PhDs shows that the centre is strategically involved in the education of young people towards their highest academic degree. The PhD work is then carried out with one or several companies in the GHz centre project. The goal should stimulate mobility of people, in particular hiring of new PhDs in industry but also short-term stays of PhD students at companies in the framework of joint projects carried out in the centre.

Year	Action	Documentation	Comment
2017	Recruitment of new PhD students The PhD students shall perform studies in the projects which are both scientifically rewarding and transferable to company partners Industrial co-supervision and mentor programs are encouraged from Chalmers Follow up indicators for MSc and lic	In the project plans, it must stand clear that PhD students are involved. Use indicators of MSc and Lic to follow the path towards PhD Reporting to board Annual report to Vinnova	
2018	PhD students will meet industry at project and centre meetings to market themselves Follow up of indicators: MSc and lic	Reporting to board Annual report to Vinnova	
2019	Follow up of indicators: MSc and lic Questionnaire to PhD student on working in GHz Centre projects.	Reporting to board Annual report to Vinnova	
2020	Follow up of indicators: MSc and lic	Reporting to board Annual report to Vinnova	
2021	Follow up of indicators and goals Follow up of GHz alumni and their employers	Reporting to board Annual report to Vinnova Five-year report to Vinnova (Spring 2022)	

2 Centre Partners

2.1 *Hosting academic partner*

Chalmers University of Technology (556479-5598), Gothenburg, Sweden
Contact: Head of MC2, Mikael Fogelström, mikael.fogelstrom@chalmers.se

Three departments at Chalmers are involved in GHz Centre:

- Department of Microtechnology and Nanoscience (MC2)
  Microwave Electronics Laboratory.
  THz and Millimetre Wave Laboratory
  Key faculty involved: Profs. Christian Fager, Jan Grahn, Jan Stake, Herbert Zirath
- Department of Electrical Engineering (E2)
  Communication Systems Group
  Key faculty involved: Prof. Thomas Eriksson
- Department of Computer Science and Engineering
  Division of Computer Engineering
  Key faculty involved: Dr. Lars Svensson

GigaHertz Centre belongs to the Area of Advance Information and Communication Technology (AoA ICT) at Chalmers. The AoA Director of ICT is Prof. Ivica Crnkovic.

2.2 *Industrial Partners*

Ericsson AB (556056-6258), Sweden
Ericsson is the world's leading provider of communications technology and services. Ericsson intends to participate in projects on efficient transceivers, linear receivers and thermal management. Ericsson will provide in kind contributions to three of the projects and also be active in the board. The know-how and potential IP from the planned projects can be of importance for 5G transceiver development at Ericsson.

Contact person: Peter Olanders, Research Leader, peter.olanders@ericsson.com

Gotmic AB (556759-4709), Gothenburg (SME)
Gotmic is a high frequency millimetre-wave company with the vision and mission to make high frequency MMIC chips affordable. Gotmic provides competence, tape-out possibilities and components to GHz Centre. Through the partnership, Gotmic intends to expand its know-how in systems and packing of relevance for its business.

Contact person: Trajan Badju, CEO, trajan.badju@gotmic.se

Infineon Technologies AG, Villach, Austria
Infineon Technologies offers semiconductor and system solutions for automotive, industrial and multimarket sectors. In GHz Centre, Infineon is interested to contribute to and participate in research in transmitters for applications in 5G mobile communications and radar and the project on thermal management. Both component- and system-related research in microwave devices, measurement, modelling, signal processing and digital CMOS design are of interest. Also Infineon is interested to join the Board.

Contact person: Franz Dielacher, Manager, franz.dielacher@infineon.com

Low Noise Factory AB (559016-9826), Gothenburg, Sweden (SME)
Low Noise Factory (LNF) is a high-tech spin-off from Chalmers. The business area is cryogenic low noise amplifiers. LNF intends to to take an active part in the project on Integrated THz Systems. LNF will contribute to design, test and measurement plus hardware packaging and evaluation. LNF will be active in the Centre Board. Successful project outcome for Low Noise Factory will lead to a new generation of modules for customers requiring utmost performance in microwave receivers, e.g. in space and scientific sensor systems.

Contact person: Niklas Wadefalk, CEO, niklas.wadefalk@lownoisefactory.com

National Instruments Corporation, TX., USA
National Instruments Sweden AB (556430-8384)

National Instruments RF provide integrated hardware and software platforms for solutions in a range of applications. The reason for participating in GHz Centre is to understand future test and measurement techniques for next generation radio technology through the development of a testbed for prototyping and validation of new communication technologies. NI intends to provide in-kind work and material contributions to the development of testbeds in the transceiver activities.

Contact person: Leif Johansson, National Instruments Sweden AB leif.johansson@ni.com

Omnisys Instruments AB (556454-6686), Gothenburg, Sweden (SME)
Omnisys engages in custom design projects, incorporating advanced analog, microwave, ASIC and power electronics, in particular for advanced scientific THz subsystems in space. In GHz Centre, Omnisys is involved in Schottky diode sub-mm wave component development, integration and testing. At Chalmers, Omnisys is interested in the design expertise, the measurement and modelling capabilities (in particular noise performance), Schottky diode mixers and functional integration of components > 100 GHz.

Contact person: Martin Kores, CEO, mk2@omnisys.se

Qamcom Research and Technology AB (556795-8003) Gothenburg, Sweden (SME)
Qamcom Research and Technology AB (Qamcom) is a technology house with a high competence in signal processing and hardware for wireless communication. This application is currently undergoing a paradigm shift towards multiple transmitters and receivers per network node, operating at mm-wave. Qamcom has an interest to contribute to this paradigm shift by participating on projects on efficient and linear transmitters. Qamcom can contribute industrial knowledge and building practice and measurement expertise. Qamcom is interested to join the GHz Centre Board.

Contact person: Robert Hedström, robert.hedstrom@qamcom.com

RUAG Space AB (556134-2204), Gothenburg, Sweden
RUAG Space AB in Sweden specializes in highly reliable on-board satellite equipment including computer systems, antennas and microwave electronics, and adapters and separation systems for space launchers. The primary interest from Ruag Space is to enhance competence

in microwave electronics for space, e.g. assessment of novel semiconductor devices. Ruag can support with competent engineering staff as well as measurement facilities.

Contact person: Paul Häyhänen, General Manager, PU MW paul.hayhanen@ruag.com

Saab Aktiebolag (556036-0793), Sweden
Business unit involved:
Saab, Gothenburg, Sweden

Saab Electronic Defence Systems is a leading supplier of airborne, ground-based and naval radar and sensor systems featuring advanced phased array systems. Saab is interested to continue its involvement in new state of the art microwave components and technology for potential usage in future radars. Saab will contribute with qualified personnel to the projects where Saab participates, e.g. through design and testing.

Contact person: Johan Carlert, Technology Strategies, Microwave and Antennas, johan.carlert@saabgroup.com

Research Institutes of Sweden - RISE
(former SP Technical Research Institute of Sweden (556464-6874)), Borås, Sweden

SP Technical Research Institute of Sweden (SP) applies its internationally leading competence to the development and evaluation of technologies, material, products, and processes to meet its customers' needs and provide an effective link between research and commercialisation.

SP Measurement Technology is participating in measurement and modelling on Thermal Management and Integrated THz Systems. Preliminary, SP will provide one senior scientist and employ one graduate student for the projects.

Contact person: Per-Olof Hedekvist, Manager per.olof.hedekvist@sp.se

United Monolithic Semiconductors, Ulm, Germany
United Monolithic Semiconductors (UMS) designs, produces and markets leading edge RF, microwave and millimetre wave components and components and integrated circuits (ICs) for the Telecom, Space, Defence, Automotive and ISM Industries.

Contact person: Hervé Blanck, Technology manager. Herve.Blanck@UMS-ULM.DE

Wasa Millimeter Wave AB (556719-1662) (Micro business <5 employees), Gothenburg, Sweden

Wasa Millimeter Wave (Wasa) is a spin-off from MC2 at Chalmers. Wasa Millimeter Wave develops and manufactures compact mm- and sub-mm wave sources, mixers and amplifiers. Wasa will design circuit demonstrators in the device technologies available from Chalmers Nanofabrication facility. Wasa will also work on novel integration and thermal management. Wasa will provide own personnel and also equipment such as broad band signal generators.

Contact person: Tomas Bryllert, CEO, tomas.bryllert@wmmw.se

3 Centre Management and Organisation

The governance of GHz Centre is stipulated by a consortium agreement (CA) signed by all partners for 2017-2021. The CA also regulates IPR, confidential information, and partners joining or leaving the centre collaboration. In addition, Chalmers will sign an agreement with all involved Chalmers-staff to regulate the so-called teacher's exemption stipulated by Swedish law.

3.1 One consortium of two centres: GHz Centre and ChaseOn

GHz Centre will together with the antenna system centre ChaseOn, hosted by Chalmers at the department of Signals and Systems, form a joint consortium. This was decided 15 September 2016, at a meeting between ChaseOn and GHz Centre stakeholders. *GHz Centre and ChaseOn will still run as independent competent centres with separate operational plans, economies and reporting to Vinnova.* The background for this joint consortium is described in Section 5. Vinnova has approved this arrangement.

There are strong reasons to form a joint consortium: Technical (microwave and antenna communities come closer and closer), strongly extending the network of competence and partners and finally, to enable potential new research between partners in the two centres. This is the first time a research consortium consisting of two competence centres is formed in Sweden.

General Assembly
The partners in the two centres form a General Assembly (GA). The GA elects the steering board. Nominees for the board will be requested from partners by Chalmers. The President of Chalmers also appoints his/her own candidate.

International Scientific Advisory Board
The International Scientific Advisory Board (ISAB) consists of well-reputed scientists in academy, institute or industry outside Sweden of relevance for GHz Centre and ChaseOn. The members are appointed by the Board after proposals from Chalmers faculty involved in GHz Centre and ChaseOn. The ISAB is informed about all activities and results coming out of the centres. The task of the ISAB is to review and advise the Board and the Directions on the standing of GHz Centre and ChaseOn in an international context both from academic, industrial and management viewpoint.

The ISAB for GHz Centre and ChaseOn year 2017-2021 appointed by the Board consists of:

- Prof. Christoph Mecklenbräuker, TU Vienna — ChaseOn
- Prof. Danielle George, Univ. Manchester — GHz Centre
- Prof. Riana Geschke, Univ. of Cape Town — ChaseOn
- Prof. Wolfgang Heinrich, FBH, Berlin — GHz Centre

Below is an illustration of how the joint consortium GHz Centre and ChaseOn will be organized :

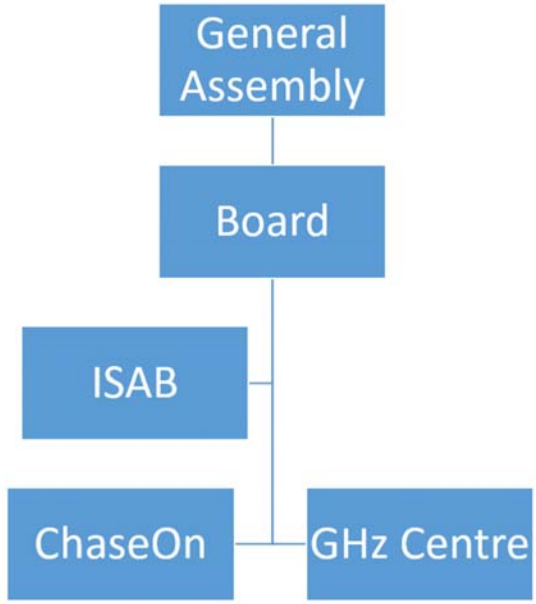


Figure showing one consortium of two competence centres, GHz Centre and ChaseOn. The agreement, general assembly, Board and ISAB are jointly for the two centres. The operation (research projects), economy and reporting to Vinnova are separated between the centres.

Steering Board

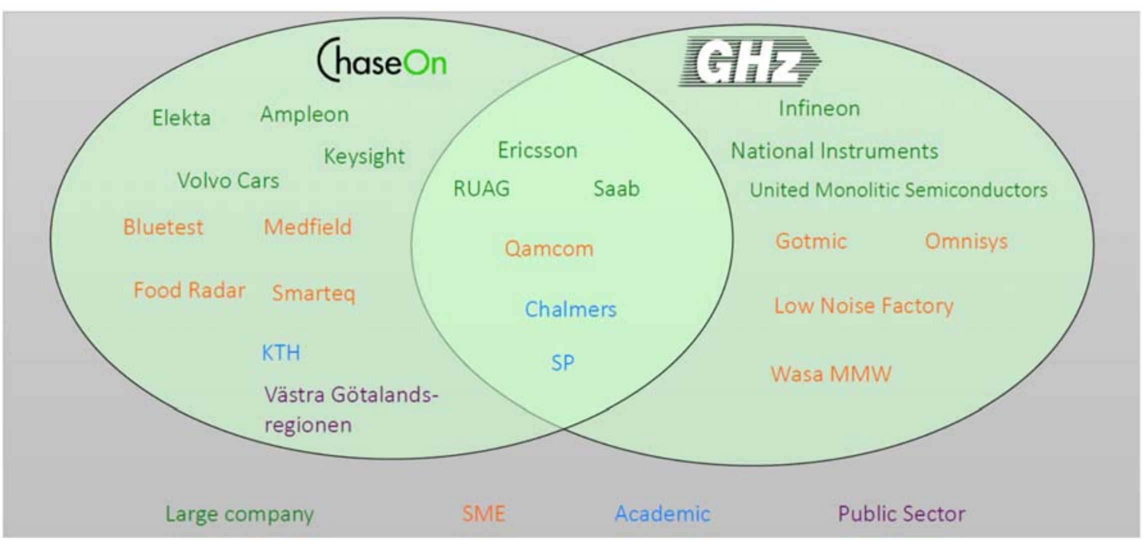
GHz Centre and ChaseOn held their first GA on 2nd February 2017. The Steering Board 2017-2021 elected by the partners consists of:

- Anna Aspgren, Chalmers (appointed by President of Chalmers) Vice Chair
- Franz Dielacher, Infineon
- Freek van Straten, Ampleon
- Golaleh Ebrahimpur, Chalmers Industriteknik
- Gunilla Karlsson, Volvo Car Corporation
- Hervé Blanck, UMS
- Ivica Crnkovic, Chalmers
- Joel Schleeh, Low Noise Factory
- Johan Carlert, Saab
- Kristina Edsberg, EQR AB
- Leif Johansson, National Instruments
- Maria Wargelius, Ericsson
- Martin Kores, Omnisys Instruments
- Michael Dieudonne, Keysight Technologies
- Peter Olanders, Ericsson Chair
- Stella Bevilacqua, SP/RISE
- Ulrika Larsson, Ruag Space

Partners and projects in GHz Centre and ChaseOn
23 partners make up the joint consortium. Of these, 5 are common for the two centres. The total matrix of GHz Centre and ChaseOn partners and their involvement in projects is illustrated below:

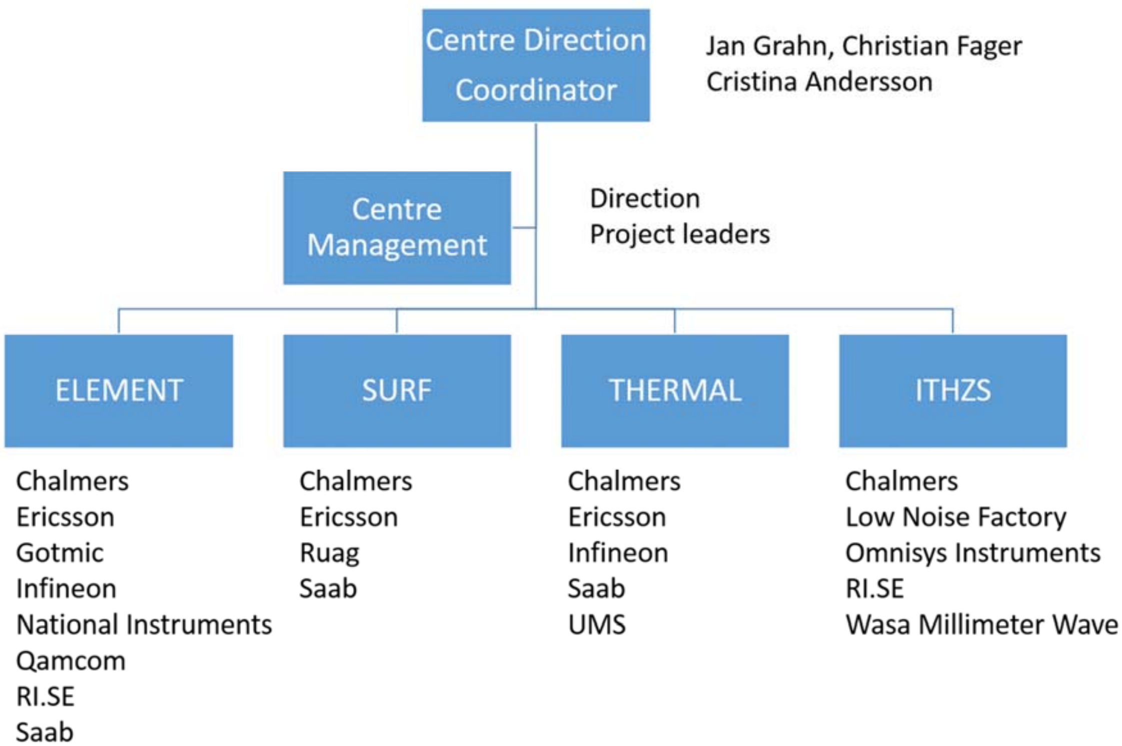
Partner	ELEMENT	SURF	THERMAL	ITHZS	Hyperth.	Sensor Sys	iAA	MANTUA	V2X
Chalmers	X	X	X	X	X	X	X	X	X
Ampleon					X				
Bluetest AB								X	X
Elekta Instrument AB					X				
Ericsson AB	X	X	X				X	X	X
Food Radar AB						X			
Gotmic AB	X								
Infineon Technologies	X		X						
Keysight Technologies					X				
Kungliga Tekniska Högskolan							X		
Low Noise Factory				X					
Medfield Diagnostics AB						X			
National Instruments Corporation	X								
Omnisys Instruments Aktiebolag				X					
Qamcom Research and Technology AB	X							X	
Ruag Space		X					X		
Saab Aktiebolag	X	X	X				X		
Smarteq Wireless AB									X
SP Sveriges Tekniska Forskningsinstitut	X			X					X
United Monolithic Semiconductors			X						
Volvo Car Corp									X
Västra Götalandsregionen					X	X			
Wasa Millimeter Wave AB				X					

Yellow columns: GHz Centre projects. Green columns: ChaseOn projects.



3.2 *GHz Centre management and organisation*

The GHz Centre is organised according to the picture below:



Centre Direction

The centre direction consists of a centre director and a deputy centre director. The centre direction is responsible for leading, execution and reporting of the activities according to the plan of the centre.

Appointed Centre Director: Jan Grahn, Chalmers
Appointed Deputy Centre Director: Christian Fager, Chalmers

Centre Coordinator

The coordinator supports the direction with progress monitoring, developing the network, contacts with Vinnova and partners, and participates in the executive meetings such as board meetings and management meetings.

Appointed Centre Coordinator: Cristina Andersson

Centre management

The centre direction of GHz Centre appoints leaders and deputies for the projects. These people form a centre management team of the centre. The group align and inform each other on the activities in the operational plan and the technical progress in the project.

Projects
The research operation in the GHz Centre is carried out in pre-defined projects between Chalmers and partners according to the research programme, see Section 4.

Since involvement in a project is associated with obligations and rights, the definition of a project is accurately formulated according to a plan template formulated by the direction. A result reported in GHz Centre is therefore always associated with a specific project. For each project, the commitment from all ingoing partners are defined in working-hours and formulated in the project plan containing the technical planning, objectives, milestones and goals for all partners. Progress and updating of the plans are made once a year.

3.3 *Forms of collaboration*

GHz-ChaseOn direction
The centre direction in GHz Centre is responsible to regularly meet with the direction in ChaseOn. The task is to evaluate and initiate common activities, directions, and opportunities made possible by the centres which then can be taken up with and reported to the common board.

Projects
The GHz Centre is based upon joint collaboration between researchers from Chalmers and industrial partners for every project. Hence the project plan and its follow-ups is a common formulation where the total working effort and commitments are made transparent to all partners. The GHz Centre is planned to stimulate high personal mobility among partners, e.g. easy access for industry to Chalmers through the establishment of a physical hub at floor 6 at MC2, Chalmers.

The direction will actively work to have the projects to learn from each other and thus to avoid “project silos”. This is alleviated by the fact that several companies are active in more than one project and that also Chalmers faculty can be assigned to several projects. Also research infrastructures such as laboratories are jointly used by the partners.

Partners participating in different programs and projects gain knowledge from each other through the common seminars, workshops, centre days, invention and manuscript disclosures and webpage as given in the communication strategy. Some of the activities such as seminars and centre days are open also for non-partners. Furthermore, the management group meets regularly to share information and look for synergies between the projects. Finally, some of these interactions will be arranged jointly with the ChaseOn Centre meaning a multiplication of potential collaboration opportunities in a large network of partners, people and competences.

3.4 *Plan for equality of opportunity*

The research area of microwave technology and techniques is an area strongly dominated by men both in academia and industry. During the years, we have therefore actively recruited female students to increase the equality. As a result, we now have 40% female PhD students when closing GHz Centre in Stage 4 (2016). The previous goal of at least 10 females out of 70 involved in the GHz Centre is therefore achieved when summing up the activity, making female engineers and researchers 15% of the total workforce in the Centre. In comparison, this number was 5% ten years ago when starting GHz Centre 2007. However, there is still a very large depletion of female researchers and engineers at the involved people from companies in the centre. Chalmers will therefore encourage industry to engage more female engineers with Chalmers staff. At Chalmers, the university suffers from too few female professors in the faculty, in particular in the field of microwave engineering at the host department MC2. The Centre Direction of GHz Centre has constantly reminded the Head of Department and Heads of involved Laboratories about this challenge and will continue to do so also during 2017-2021.

The new Board of GHz Centre together with ChaseOn has more than 40% female representation according to the decision by Vinnova. This will serve as an important inspiration and good example for Chalmers and many companies.

The GHz Centre gender goal is to reach at least 15 involved female PhD students, researchers and engineers among all involved staff and students in the GHz Centre when ending 2021. Out of an estimated 65 people involved in the Centre, this would mean mean more than 20% females, i.e. a 4 times improvement over 15 years.

The goal is a common task for all the partners involved, not only for Chalmers. Our main action is the continuous search and recruitment of talented female students and researchers in all recruitment campaigns to GHz Centre projects and boards from the partners. Chalmers intends to discuss the lack of professional women in the microwave engineering field with industrial partners and how such issues are tackled among the companies. Important inspiration and advice can be find from e.g. Women in Engineering events at EuMW and IMS. The plan for equality of opportunity is taken up as a point on the agenda every second Board meeting and reported in the annual progress as well as in the regular Vinnova reporting.

3.5 *The Centre in the University Organisation*

Chalmers is a matrix organisation with at present seventeen Departments (decided to be reduced to twelve from May 2017) and eight Areas of Advance. The departmental re-organisation of Chalmers will neither affect the hosting of GHz Centre, nor the joint consortium with ChaseOn. GHz Centre is active within three of the current departments: MC2, E2 (former Signals and Systems (S2)) , and Computer Science and Engineering (CSE). The host is MC2. The Centre Director and deputy Director will be employed by MC2, Chalmers.

GHz Centre is part of the Area of Advance Information and Communication Technology (ICT) at Chalmers. The AoA ICT will be a platform for GHz Centre (and the ChaseOn) to regularly communicate with other Chalmers – industry consortia, e.g. Software Centre. This is essential to synchronise and establish common practice from Chalmers to various company sectors participating in Chalmers research activities.

The GHz Centre will be a physical Centre where both industry and Chalmers have a common meeting point at floor 6 at MC2. Dedicated office spaces are therefore offered for the Centre at the Microwave Electronics Laboratory and THz and Millimetre Wave Laboratory, but also at the Communication System group at E2. The industry will have four places dedicated for their personnel to use. Signs and posters will show the way in the MC2 house to the GHz Centre. Chalmers will make it straightforward for industrial partners to come and work in the Centre and to interact with the academic researchers.

The contact with the upper management of Chalmers will be carried out with the Chalmers representative in the Steering Board appointed by the President of Chalmers. The Centre Director is also expected to have frequent contacts with the Department Heads of MC2, E2, and CSE as well as the Area of Advance Director for ICT, and the Vice President for utilisation and innovation at Chalmers.

3.6 *Centre Communication Strategy and Plan*

The communication serves the following purposes:

- Internal communication within a project: Joint projects between partners from different organisations, countries etc must be made efficient in order to fulfil the commitments in the project plan.
- Internal communication between projects: This is essential for the meaning of a centre: Communication between projects is essential to develop the common Centre objectives. It is also important for various partners to learn from progress in other areas which may be of interest when revising plans.
- External communication within Chalmers: The university has many centres and new initiatives are constantly launched. The partnership in a joint consortium between GHz Centre and ChaseOn offers a unique opportunity to highlight maybe the largest constellation of companies in one Chalmers-industrial collaboration. Microwaves and antennas (systems) are two particular strengths in the Chalmers ICT research. This should be used to create “best practices” and departmental policies how Chalmers and industry is working efficiently together.
- External communication outside Chalmers: GHz Centre and ChaseOn shall create some branding in the research community. The details and effort of this are still to be discussed.

Internal communication

- The project meetings organised by the project leaders at least twice per year will serve as the most important internal communication between the ingoing partners for recent technical results. These meetings are reported to the direction. Participation by telephone and/or Skype for Business will be offered for remote attendees.
- The management group is the most important group to bridge the projects, share experiences and propose changes. These meetings are typically held once every month. The management group is a link between the researchers at Chalmers and the Board.
- Mobility of researchers. Chalmers, MC2 will offer GHz Centre constant access to four office places for industry in the office area floor 6 at MC2 and E2. Chalmers researchers and students are encouraged to spend time at the member companies during shorter periods if such possibilities show up in the projects.
- The Steering Board meeting three times per year will serve as a source of internal information and communication between the partners in the strategic questions.
- Access to Chalmers box.com area is made for external partners for documents and slides from meetings etc. This is made possible by a password protected home page.

The resources for these activities are normally taken from the projects. The office space for industry is a substantial contribution from Chalmers to GHz Centre.

Dissemination of inventions or manuscripts prior to publication

According to the consortium agreement, Chalmers is responsible to disclose results prior to publication. Chalmers discloses information either in the form of a Manuscript or Invention. The disclosure is e-mailed to designated contact persons among GHz Centre partners. The subject is: "GHz Centre Disclosure". The Manuscript disclosure is normally a draft meant for submission to either a conference or a scientific journal. An Invention disclosure is to reveal ideas or results from GHz Centre projects having the potential of being patentable. If any partner wishes to delay the publication, Chalmers will as owner of results start an immediate negotiation with the Partner how to alter text as not to reveal confidential information or how to protect and register patentable results for maximising the exploitation potential of the invention.

The outcome of each disclosure of Manuscript or Invention will be reported to Steering Board and in Progress Reports. This reporting constitutes a major indicator of progress in a project.

At the first Steering Board meeting, each partner will give input of the names from its organisation to be put on the official disclosure emailing list.

External communication

The external communication is carried out according to the following points:

- Publications and presentations must be made with the affiliation *GigaHertz Centre*. This is important for branding the Chalmers-industrial results in the scientific community and highlighting the partnership involved including Vinnova as governmental body.
- The GHz Centre will arrange one open grand meeting every year with ChaseOn where the on-going research is reported. Invited external speakers will be actively sought after, e.g. for certain timely wireless topics of joint interest for Chalmers and industry. A more detailed time plan of official meetings will be decided with the ChaseOn direction during Spring 2017
- A joint seminar series will be arranged with ChaseOn.
- Technical workshops will be arranged by the projects, if possible in collaboration with ChaseOn antenna centre and the local company cluster Microwave Road.
- We will maintain a list of e-addresses for the microwave community members with a potential interest in GHz Centre.
- One printed folder and one set of viewgraphs will be prepared highlighting the mission, projects and partners of GHz Centre.
- At relevant Swedish events such as Swedish Microwave Days, presenting a roll-up poster for showing the Centre research and partners. This GHz Centre roll-up is normally displayed at the entrance of the hosting department MC2.
- A homepage www.chalmers.se/ghz describing the GHz Centre including published results and success stories.
- Presenting the Centre at Chalmers' and external partners request at site visits at Chalmers and outside.

The resources for these activities are normally budgeted at the Management project. Assistance at MC2 is given to GHz Centre from the Communication officer who is helping us to technically maintain and update the home page.

Communication between the GHz Centre and ChaseOn

GHz Centre and ChaseOn will have a meeting plan to regularly prepare for Centre Days, Board meetings and to discuss new ideas and possibilities emanating from the consortium.

The Directions of the two centres meet in a Director's group. This consists of the Director's and their deputies including the coordinator. The task for the Director's group is to prepare and follow up the Board meetings.

We are using a joint coordinator between the MC2 and S2 (E2) departments to facilitate meetings, reporting, arrangements and outreach.

The project leaders/principal investigators in GHz Centre and ChaseOn meet at least once every semester. This will be evaluated after the first year how such meetings can be arranged for maximum synergy.

The Director's group will take the initiative for a strategic group to prepare for the future after the Centres period. This group will be decided by the Board.

4 Research Programme

4.1 *Centre Research Profile*

The shift to scalable, highly integrated systems operating at mm-wave frequencies is a paradigm shift in the design of hardware for wireless systems and poses completely new fundamental research questions that have to be addressed before the promised advantages can be realized in future wireless system designs.

The GHz Centre research aims to develop the next generation scalable wireless hardware solutions that enables cost- and energy efficient wireless systems in communication, defence, and space system application areas. This is only possible through the unique research environment and infrastructure available in the GHz Centre. Our joint research expertise and infrastructure is ranging all the way from semiconductor device technology, to integrated high-frequency circuit design, signal processing, industrial test-bed verifications, and systems. The three projects that we define describe, in a concrete way, how the GHz Centre collaboration will enable us to address key challenges in next generation wireless transmitters and receivers for future wireless systems.

There are a number of fundamental challenges that have to be addressed in order to enable next generation highly integrated and scalable wireless hardware. These challenges can be organized into three major categories:

- *Challenge* 1: Integration and scalability
- *Challenge* 2*:* Energy efficiency
- *Challenge* 3*:* Selectivity and sensitivity

These fundamental challenges will serve as a foundation for the proposed GHz Centre research.

Challenge 1: Integration and scalability
Next generation wireless hardware solutions need to adapt to the size and volume necessary in large multi-antenna systems. The hardware size is therefore inherently limited and dictated by the wavelength. With a general trend towards higher frequencies, a very high level of functional and physical integration is required to fit all required high frequency electronics and signal processing in a strictly limited area and volume. Integrated transmitters and receiver hardware is therefore necessary, possibly involving both analog and digital functionality on the same chip. This is facilitated through the advanced Si-based semiconductor process capabilities now available. Low cost, scalable building practice and packaging solutions are also extremely important and will to a large extent determine the overall performance of the entire wireless system both in thermal, mechanical, and electrical terms. Heterogeneous packaging solutions, where highly integrated Si-based core functionality is augmented with high performance front-end circuits in III-V/III-N technologies, will enable also challenging performance specifications to be met. Waveguide integrated solutions, e.g. using membrane technology, is opening the possibility for scalable hardware also in the sub-mm-wave and THz frequency regimes.

Testing and verification is becoming a major challenge with increased integration, higher frequencies, and more wideband signals. In absence of well-defined connectorized 50Ω

interfaces, completely new frameworks for measurement, simulation, and modelling need therefore to be developed to relate circuit, component, and package/antenna characteristics to system performance in highly wideband integrated wireless hardware solutions.
The inherent complexity of realizing future wireless systems, possibly involving hundreds of channels, will require a distributed approach with autonomous transmit/receive blocks. Each unit must therefore have built-in functionality to characterize and compensate for its impairments, with minimum involvement of central resources.

The high level of integration in combination with low energy efficiency at high frequencies leads to significant heat dissipation challenges. Excessive temperatures reduce reliability, sensitivity, and output power and must therefore be carefully analysed and accounted for.

Challenge 2: Energy efficiency
As mentioned above, severe energy consumption and heating problems will occur with currently available hardware technology and system architectures. Thermal effects due to inefficient hardware is therefore constraining the wireless system design, and can in the worst case prevent energy efficient system solutions from being realized (e.g. massive MIMO for 5G). One of the most important research challenges is therefore to increase the energy efficiency of next generation wireless hardware.

The transmitter is usually dominating the energy consumption in wireless hardware designs. Efficient transmit circuits (PAs, DACs, IQ modulators, etc.) are critical components and must be co-designed with digital signal processing functions and the system architecture to minimize the overall energy consumption for given application requirements. In fact, the increased complexity in future wireless systems cause an increasing amount of the energy to be consumed by digital signal processing and high-speed interface circuits. Scalable energy efficient wireless hardware solutions must therefore balance the analog and digital power consumption. Thermal management is an integral part of the overall hardware design and new analysis techniques are needed to treat the electrical, mechanical, and thermal effects in a unified framework. Downscaled CMOS and BiCMOS semiconductor processes that enable on-chip integration of analog mm-wave circuits, digital signal processing, and data converter (DAC/ADC) functions is opening new possibilities to improve overall energy efficiency in wireless hardware and systems.

At high sub mm-wave frequencies, the energy consumption is dominated by the need for high power local oscillator sources. With conversion efficiencies as low as a couple of percent, new energy efficient multiplier and amplifier solutions operating beyond 100 GHz are vital to resolve the heat dissipation problems and enable scalable and cost efficient sub mm-wave space and satellite systems.

Challenge 3: Sensitivity and selectivity
In applications ranging from mobile communication to radio astronomy and radars, wireless receivers must be able to detect weak signals in presence of strong interfering signals and noise. A high level of integration will make it challenging to achieve high quality filtering at high RF/mm-wave frequencies. Clearly, next generation wireless hardware will imply completely new trade-offs between sensitivity, selectivity, and energy consumption.

Spatial filtering, through analog or digital beam-forming, is one technique that can be explored to suppress interference and to relax the need for high quality RF/mm-wave filtering. Further filtering has to be performed at intermediate frequency or at baseband by a combination of analog and digital techniques. Since a large part of the filtering will move to the IF side, the interference level in the RF circuits is still expected to be higher than in today's systems. This will push significant linearity and dynamic range challenges for the receivers used and require a careful co-design of the entire receiver chain – from low noise amplifier to A/D converter, considering its use in a large multi-antenna environment.

Scientific- and defence applications will in some cases require extreme sensitivity and selectivity requirements only possible to meet with dedicated transistor technologies (InP or GaN). Highly-integrated multi-chip receiver solutions is very desirable in multi-array systems.

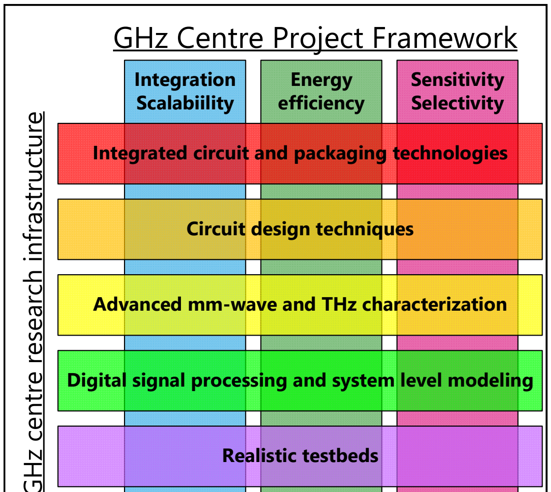
Overall, to achieve high linearity and sensitivity in multi-antenna receivers involves complicated mm-wave circuit design trade-offs between linearity, energy consumption, and noise that which has to be co-designed with application specific signal processing to reach the desired overall sensitivity and selectivity in future wireless receivers.

4.2 *Research projects*

The three hardware challenges described above serve as a common framework for the research projects in the GigaHertz Centre. Each project will, in different ways, contribute to address one or more of these common challenges. This will promote significant interactions between projects, members, and application areas thus avoiding project silos or sub-centres. Following this approach, we will describe the four GHz centre projects that reflect the strongest industrial needs: *Efficient and linear transmitters, Smart receivers, Integrated THz systems, and Thermal effects*. In the centre duration of five years, these projects may be revised and new projects may be defined. However, the fundamental hardware challenges and project framework remain will remain.

Methodology

The overall intention of the GHz Centre is to maximize future wireless system level performance through research on next generation scalable hardware solutions. As an example, in an imaging system our target will be to develop wireless hardware solutions that maximize the image resolution, rather than necessarily minimizing the noise figure of the receiver. We will therefore adopt a holistic approach where the full research infrastructure available in the GHz centre is exploited to address the challenges in each research project.



GHz Centre will integrate research from components to test-beds to address future wireless and sensor system needs.

We have access to state-of-the art semiconductor processes and models that we will use to realize highly integrated multi-function mm-wave circuits. This will enable us to investigate scalable transmit- and receive circuit solutions targeting both high energy efficiency, low noise, and high selectivity. Advanced packaging solutions will enable us to realize complete wireless hardware modules suitable for use in system level testbed experiments.

World-class measurement capabilities will enable us to characterize the manufactured circuits and hardware modules both for noise performance and with realistic wideband modulated, high-speed digital input signals. The results serve as a basis for development of behavioural models suitable for system level modelling and analysis. In combination relevant signal processing techniques, we will be able to link hardware characteristics to system-level performance metrics. Optimization of these performance metrics (e.g. communication capacity, radar imaging resolution, energy consumption, sensor sensitivity) will guide the GHz Centre hardware development.

We will use industrial and Chalmers test beds to evaluate the validity of the system level analysis predictions and to demonstrate the wireless hardware research results in realistic application scenarios. Other industrial test beds (e.g. Ericsson 5G) and existing products will be used as a reference for benchmarking the GHz Centre results. In line with our vision, the target is always to demonstrate new wireless hardware that enable much better system performance compared to existing solutions. Thus, the test bed results will serve as a basis for faster industrial exploitation of the GHz Centre research results obtained.

All the projects are described in detailed plans set up according to a certain GHz Centre template. The plans have been approved by all partners and are updated every six months.

Equality of opportunity in the research programme

Each project is having an obligation to increase gender equality plan and action through recruiting of females in Master, PhD students and postdocs. This will be followed up by the management group and reported to the board at each meeting.

Efficient and Linear Millimeter Wave Transmitters (ELEMENT)

Research partners
Chalmers, Ericsson, Gotmic, Infineon, National Instruments, Qamcom, RISE, Saab

Project leader: Christian Fager, Chalmers
Deputy project leader: Lars Svensson, Chalmers

Motivation
Transmitters for future multi-antenna millimetre wave systems need to be highly integrated and energy efficient to meet performance, cost, and reliability requirements. Exploration of downscaled silicon technologies, which combine high speed digital processing and millimetre wave RF performance, will be a key to address these needs. However, to fully utilize the potential of these technologies, new transmitter architectures need to be considered. Digitally intense transmitters are therefore envisioned where traditional building blocks that today are implemented in separate analog building blocks will be designed as part of a highly integrated solution. To maximize the performance and energy efficiency of multi-antenna millimetre wave transmitters in this paradigm will require a deep understanding of analog and digital design, measurement, and building techniques, both at circuit and system level.

Objectives
This project will investigate innovative multi-antenna transmitter solutions that address the need for high efficiency and flexibility in future millimetre wave communication and sensor systems. This is broken down into the following specific project objectives.

- Investigate digitally intense transmitter solutions for maximum system performance
- Co-design of array signal processing with (Bi)CMOS transmitter circuits
- Mixed digital and analog circuit design techniques for improved efficiency and reconfigurability
- Adaptive on-chip self-linearization and self-optimization techniques
- Package-level integration and co-design between CMOS and GaN/GaAs circuits
- Develop methodologies for over-the-air characterization of transmitter circuits
- Build transmitter system demonstrators
- Energy efficient linearized MIMO communication transmitter
- Wideband mm-wave MIMO radar (with SURF project)

Project outcome
- State-of-the art in energy-efficiency for linear millimetre wave MIMO transmitter systems
- Understanding optimum analog and digital processing co-design in linear CMOS transmitter circuits
- High performance packaged transmitters using co-design of silicon- and III/V and III-N circuits
- Methods for over-the-air characterization of multi-antenna transmitter circuits
- Updated industrial roadmaps for integrated transmitter development

Smart Receivers for Future Linear RF Systems (SURF)

Research partners
Chalmers, Ericsson, Ruag and Saab

Project leader: Koen Buisman, Chalmers
Deputy project leader: Thomas Eriksson, Chalmers

Motivation
Future many-antenna mm-wave RF systems will require receiver line-ups that are linear, power efficient, compact and flexible. Especially reduced filtering possibilities at the front-end will allow interfering signals to impinge directly on the non-linear components in these line-ups, and the dynamic range of the ADCs will suffer in such scenarios. To cope with this situation, ultra-linear performance and high dynamic range will be required. As a consequence designing for worst-case performance will result in too power hungry solutions. Therefore new, flexible, adaptive, smart receiver line-ups need to be invented that can cope with all circumstances in such aggressive wireless environments, while simultaneously meeting all performance requirements of future RF systems.

Objectives
This project will investigate future receiver solutions for many antenna mm-wave arrays for RF communications, sensor and measurement systems. This has been broken down in the following objectives:

- Investigate and improve flexibility and linearity bottlenecks in current typical receiver line-ups, without compromising power consumption constraints.
- Study trade-offs between analog/digital compensation methods or combinations thereof. Resulting in co-design between analog hardware and digital processing for the hardware demonstrators.
- Built integrated receiver demonstrators using the obtained knowledge:
- Highly linear, flexible receivers
- Wideband MIMO radar system (with ELEMENT project)

Project outcome
- 10 articles in high impact journals, half of which co-authored with industry.
- 15 conference papers at high-impact conferences, half of which co-authored with industry.
- 2 invited or tutorial presentations at good conferences.
- 2 co-organized workshops on distortion mitigation and linearity improvement.
- 2 PhDs
- State-of-the art mm-wave integrated SiGe/CMOS receiver hardware demonstrators showing improved dynamic range performance under power consumption constraints.
- Methods for over-the-air characterization and calibration of receivers.
- Understanding of trade-offs in co-design of analog hardware with digital signal processing.

Thermal Effects (THERMAL)

Research partners
Chalmers, Ericsson, Infineon, Saab, UMS

Project leader: Mattias Thorsell, Chalmers

Motivation
The trend for both mobile communication systems and microwave sensors is the use of more transceivers as well as higher level of integration of these. The heating elements (mainly power amplifiers) will hence increase in number and be more densely packed. The available area for heat sinks will at the same time be reduced due to the move to higher operating frequencies. Furthermore, the higher level of integration will lead to multiple amplifiers on the same die, resulting strong thermal coupling between different transceivers, which needs to be accounted for. It can therefore be foreseen that the electronics in these systems will operate at higher temperatures compared to less integrated systems, hence reliability will be an important issue.

Objectives
- Electro-thermal effects at transistor/die level
- Electro-thermal characterization with electrical and thermal stimuli
- CAD and TCAD transistor modelling
- Integration of heat spreaders and/or heat sinks
- Thermal effect compensation
- Thermal effects in multi antenna systems
- Dynamic thermal coupling between transceiver blocks
- Reliability
- Long term reliability of electronics in multi antenna systems in harsh environments
- Fault analysis on transistor level

Project outcome
- 2 new PhDs
- 20 articles in high impact journals or major peer reviewed conferences
    - 50 % of the articles co-authored with industrial partners
- 1 test-bed for electro-thermal characterization enabling both electrical and thermal stimuli

Integrated Terahertz systems (ITHZS)

Research partners
Chalmers, Low Noise Factory, Omnisys Instruments, RISE, Wasa Millimeter Wave

Project leader: Peter Sobis, Omnisys Instruments
Deputy project leader: Tomas Bryllert, Chalmers

Motivation
For microwave as well as for THz systems, operating close to the fundamental noise limits, the lack of commercially available components that meet such stringent system requirements is evident. Chalmers has together with industry developed unique cryo LNA and Schottky diode device process lines able to meet such requirements. Ultra-low noise amplifiers are needed for read out of qubits in quantum computers, as well as in radio astronomy and remote sensing. THz sensors can be used for molecular spectroscopy in atmospheric sensing, radio astronomy as well as in industrial applications and radar. The challenge is to make these systems more compact and cost effective – through higher integration level, we expect the new industrial applications of this technology.

Objectives
- Device and circuit development
- HEMT device scaling at 70 nm and below. Integration in MMIC process.
- Ultra-low power HEMTs for cryo LNAs
- A +2 THz monolithic Schottky membrane MMIC process.
- Efficient Schottky membrane multiplier MMICs up to +1 THz
- Integration
- Ultra low-noise LNAs at 118 and 183 GHz
- Super integrated multi MMIC radiometer/radar frontends in a single housing
- Explore new packaging technology (e.g. laser cut stencils, 3D printing)
- Demonstrators:
- 183 GHz LNA, 1.2 THz multiplier, 1 THz radar transceiver, 2 THz receiver, cryogenic C-band LNAs for qubit readout circuits in quantum computers
- Measurement techniques
- Develop measurement techniques with VNAs up to 1.5 THz
- Radiometer characterization in quasi-optical systems
- Develop test/calibration methods for active systems including RADAR and spectroscopy

Project outcome
- Hardware outcome; 183 GHz LNA module, 2 THz Receiver, 1 THz Source/Transceiver Module
- Publications; 5 journal, 10 peer reviewed conferences; 20 workshops. Tentative titles “Cryo LNAs above 100 GHz”, “Waveguide embedded TRL calibration of Schottky diode membrane MMIC above 1 THz”
- SME Growth
- 2 PhDs

5 Changes in plans in comparison to the operational plan for Stage 4 and the application of GHz Centre

5.1 *GHz Centre and ChaseOn*

In the operational plan for GHz Centre Stage 4 (2015-2016), the future of GHz Centre after 2016 was formulated. The changes from this plan are here described.

It is essential to underline that competence centres in Sweden is dependent upon the governmental funding. As a result, the strategy for the future is strongly connected to the choice of the public authorities in how to fund such instruments. When the operational plan for Stage 4 was formulated, the intentions from Vinnova with regard to the future of competence centres were not known.

In the Stage 4 plan, we formulated a common vision with Chase antenna systems centre. In fact, these discussions were started already late 2012 in a formal task force. During 2013-2015, these discussions among Chalmers faculty and with industry were intensified and important consensus on the way forward was reached. Part of this was reported in the Stage 4 plan.

In May 2015, Vinnova called for competence centres after 2016. Part of the call was intended for existing centres from the Vinn Excellence program for continued funding year 2017-2021. The set-up of the call had an immediate consequence that GHz Centre and Chase had to apply *independently* for a prolongation. Both centres were successful in their proposals and approved for continuation 2017-2021 by Vinnova in May 2016.

After the decision by Vinnova, the main applicants for GHz Centre and ChaseOn discussed during Summer 2016 on how to take advantage of a situation with the two competence centres. Together with the stakeholders, it was proposed and decided to form a joint consortium between the two centres at a stakeholder meeting 15 September 2016. The organisation of two competence centres in one consortium is described in Section 3.

The organisation part is the major change compared to both Stage 4 plan and the original proposal. In this way, we can both operate the centres as individuals (results, reporting and economy) while taking advantage of the synergy and collaborations in a joint consortium. Note that the technical objectives have not been changed since the large majority of industrial partners as well as the key faculty at Chalmers remain the same.

Operating under the same Consortium Agreement means large opportunities for all partners the two centres to find new collaborations without the walls set up by IPR conditions, confidentially clauses etc. Since GHz Centre and ChaseOn operate are in different yet adjacent parts of the supply chain for wireless and sensor systems, the complementarity with respect to competences is excellent between the competence centres.

5.2 *GHz Centre budget – changes after negotiation fall 2016*

GHz Centre 2017-2021 was applied for January 2016 based on Letters of Intent (LoI) from the partners. After the approval of the application by Vinnova May 2016, negotiation started to form the centre. One of the partners, Ampleon BV, submitting an LoI, decided in the fall 2016 not to join the GHz Centre. Some companies increased their investment, some reduced because of updated internal priorities at the partners with respect to the involvement in GHz Centre projects. The Table below shows the difference between LoI and the final commitment as stated in the Consortium Agreement (CA) signed by the partners.

It is seen that after negotiation, the annual investment from the partners was reduced from 16.7 (cash 4.9) MSEK to 12.8 (4.7 cash) MSEK. The major source (83%) of reduction was due to Ampleon eventually not joining GHz Centre. Compared to the original application for GHz Centre, this means a total reduction of almost 12% of the investment. However, the cash portion was only marginally affected (-5%) and the industrial investment in GHz Centre is 48% of the total investment, far beyond what is required by Vinnova competence centres, *i.e.* 33%. A sizeable portion is also invested by industry in cash (39%), also far beyond what is normal for Vinnova competence centres.

See Section 7 for details on the final budget of GHz Centre.

Partner total investment per year in GHz Centre (SEK)	**LoI January 2016 (total)**	**LoI January 2016 (cash)**	**CA January 2017 (total)**	**CA January 2017(cash)**	**Difference per year (total)**	**Difference per year (cash)**
Chalmers	7 083 717	0	7 197 720	300 000	114 003	300 000
Ampleon	3 200 000	700 000	0	0	-3 200 000	-700 000
Ericsson AB (556056-6258)	3 350 000	1 000 000	2 950 000	1 000 000	-400 000	0
Gotmic AB (556759-4709)	990 000	100 000	1 140 000	250 000	150 000	150 000
Infineon Technologies Austria AG	1 710 000	650 000	1 710 000	650 000	0	0
Low Noise Factory AB (559016-9826)	1 220 000	300 000	1 220 000	300 000	0	0
National Instruments Corporation	380 400	80 000	500 400	200 000	120 000	120 000
Omnisys Instruments Aktiebolag (556454-6686)	1 500 000	500 000	1 500 000	500 000	0	0
Qamcom Research and Technology AB (556795-8003)	451 600	200 000	501 600	250 000	50 000	50 000
Ruag Space AB (556134-2204)	766 000	333 000	766 000	333 000	0	0
Saab Aktiebolag (Publ) (556036-0793)	1 700 000	850 000	1 700 000	850 000	0	0
SP Sveriges Tekniska Forskningsinstitut (556464-6874)	340 000	100 000	232 000	100 000	-108 000	0
United Monolithic Semiconductors	885 000	15 000	470 000	200 000	-415 000	185 000
Wasa Millimeter Wave AB (556719-1662)	208 000	100 000	158 000	50 000	-50 000	-50 000
Sum	**16 701 000**	**4 928 000**	**12 848 000**	**4 683 000**	**-3 853 000**	**-245 000**

Table showing GHz Centre investments in the Vinnova application (based on LoI) January 2016 and after negotiation fall 2016 leading to the CA January 2017.

6 Plans for activities beyond Vinnova funding

Given the never-ending changes in wireless industry as well as directions from the Swedish Government with respect to how to invest in science and innovation, it is still too early to predict how the GHz Centre activities will be planned after 2021.

In order to be well prepared, we will use the ChaseOn-GHz Centre Board to outline scenarios and strategies how a competence centre in microwaves hosted by Chalmers can be made attractive for the partners including Vinnova in the 2020's. The ISAB will be one of the most important bodies in such a strategic discussion. Given a 25-year long and successful collaboration between Chalmers and industry now involving more research groups and companies than ever, we believe that we are well prepared for planning our wireless future in research and innovation.

7 Financing and budget for 2017-2021

The involved staff from Chalmers and all partners is given in the Excel tables in the appendix of this document.

One Full-Time Equivalent (FTE) = one working year = 1680 h = 140 h/month

7.1 *Assumptions made for calculation of contributions inkind*

For all partners, the contribution is divided between cash, and inkind. In kind is categorized as either work contribution in hours by specified personnel (name, position) or material contribution. Work is calculated according to Vinnova standards as 600 SEK/hour for all partners excluding Chalmers. Material can be lab resources, components, foundry runs etc. This inkind must be specified in the project plan and given a specific value approved by the partners. Note that all inkind belongs to the GHz Centre under the same formal conditions as the cash contributed part.

7.2 *Chalmers contribution*

- Chalmers allocates four office spaces for external GHz Centre partners at MC2, floor 6 (3 places), and at E2 department (1 place) at full time with fully equipped EDA tools for industrial partners. This cost corresponds to the overhead cost at Chalmers for full-time employees in keeping up the infrastructure for research. The cost also includes full access to copy machines, Chalmers library and full administrative and technical support.
- Chalmers offers the THz/mm-wave/microwave measurement infrastructure for GHz Centre staff in all projects. This is one of Northern Europe's best equipped microwave laboratories with equipment worth around 100 MSEK. This facility can be used by industry 200 h per year including training using the instruments.
- Chalmers offers industry access to the Microwave Process Line at the cleanroom at MC2. This facility is strongly subsidized by Chalmers Foundation with around 10 MSEK per year. This facility can only be used by Chalmers personnel in GHz Centre.
- Chalmers spends inkind by involving MC2 administrative personnel (MoM support at Steering Board meetings, practical arrangements, economical administration, communication functions such as web page support, folder and poster material, and press releases)

The budget provided from Chalmers to GHz Centre is given as follows:

Annual in kind budget Chalmers	**SEK/h**	**Hours/yr**	**SEK/yr**
Office spaces & EDA software & support	200	6 720	1 344 000
THz lab (Industrial users)	1 000	200	200 000
THz lab (Academic users)	250	1 600	400 000
Cleanroom NFL (only academic users)	800	1 200	960 000
Sum in kind material			**2 904 000**
Faculty in kind	**FTE**	**Position**	**SEK/yr**
Thomas Eriksson	40%	Prof	840 212
Christian Fager	50%	Bitr Prof	846 047
Jan Grahn	60%	Prof	1 260 319
Jan Stake	10%	Prof	210 053
Lars Svensson	25%	Docent	379 263
Herbert Zirath	5%	Prof	105 027
Support administration MC2	35%	TA	352 800
Sum inkind work			**3 993 720**
Chalmers cash			**300 000**
Chalmers total contribution			**7 197 720**

7.3 *Industrial contribution and total income budget*

The income in SEK/year from industrial partners in GHz Centre is as follows:
The in kind cost for work is 600 SEK/h according to Vinnova standards.

Contribution per year	Work in kind (SEK)	Material in kind (SEK)	Cash (SEK)
Ericsson AB (556056-6258)	1 700 000	250 000	1 000 000
Gotmic AB (556759-4709)	540 000	350 000	250 000
Infineon Technologies Austria AG	360 000	700 000	650 000
Low Noise Factory AB (559016-9826)	720 000	200 000	300 000
National Instruments Corporation	50 400	250 000	200 000
Omnisys Instruments Aktiebolag (556454-6686)	600 000	400 000	500 000
Qamcom Research and Technology AB (556795-8003)	201 600	50 000	250 000
Ruag Space AB (556134-2204)	333 000	100 000	333 000
Saab Aktiebolag (Publ) (556036-0793)	850 000	0	850 000
Research Institutes of Sweden – RISE (former SP Sveriges Tekniska Forskningsinstitut (556464-6874))	132 000	0	100 000
United Monolithic Semiconductors	120 000	150 000	200 000
Wasa Millimeter Wave AB (556719-1662)	108 000	0	50 000
Sum	**5 715 000**	**2 450 000**	**4 683 000**

The total income budget for GHz Centre including the Vinnova cash contribution is then:

Cash contribution GHz	**2017**	**2018**	**2019**	**2020**	**2021**	**Total**	**%**
Industry	4 683 000	4 683 000	4 683 000	4 683 000	4 683 000	**23 415 000**	39%
Chalmers	300 000	300 000	300 000	300 000	300 000	**1 500 000**	3%
Vinnova	7 000 000	7 000 000	7 000 000	7 000 000	7 000 000	**35 000 000**	58%
Sum	**11 983 000**	**11 983 000**	**11 983 000**	**11 983 000**	**11 983 000**	**59 915 000**	**100%**
Total contribution GHz	**2017**	**2018**	**2019**	**2020**	**2021**	**Total**	**%**
Industry	12 848 000	12 848 000	12 848 000	12 848 000	12 848 000	**64 240 000**	48%
Chalmers	7 197 720	7 197 720	7 197 720	7 197 720	7 197 720	**35 988 601**	27%
Vinnova	7 000 000	7 000 000	7 000 000	7 000 000	7 000 000	**35 000 000**	26%
Sum	**27 045 720**	**27 045 720**	**27 045 720**	**27 045 720**	**27 045 720**	**135 228 601**	**100%**
Contribution GHz	**2017**	**2018**	**2019**	**2020**	**2021**	**Total**	**%**
In kind work	9 708 720	9 708 720	9 708 720	9 708 720	9 708 720	**48 543 601**	36%
In kind material	5 354 000	5 354 000	5 354 000	5 354 000	5 354 000	**26 770 000**	20%
Cash	11 983 000	11 983 000	11 983 000	11 983 000	11 983 000	**59 915 000**	44%
Sum	**27 045 720**	**27 045 720**	**27 045 720**	**27 045 720**	**27 045 720**	**135 228 601**	**100%**

7.4 *Project budget*

The budget per GHz Centre project per year is according to the Table below:

LEADERSHIP is for the Direction of the Centre.

Cash budget/yr						
Project	**LEADERSHIP**	**ELEMENT**	**SURF**	**THERMAL**	**ITHZS**	**SUM**
Industry	0	1 691 667	949 667	1 141 667	900 000	**4 683 000**
Chalmers	300 000	0	0	0	0	**300 000**
Vinnova	1 000 000	1 500 000	1 500 000	1 500 000	1 500 000	**7 000 000**
Sum	**1 300 000**	**3 191 667**	**2 449 667**	**2 641 667**	**2 400 000**	**11 983 000**
%	11%	27%	20%	22%	20%	100%
Inkind work budget/yr						
Project	**LEADERSHIP**	**ELEMENT**	**SURF**	**THERMAL**	**ITHZS**	**SUM**
Industry	0	1 888 000	1 183 000	1 150 000	1 494 000	**5 715 000**
Chalmers	352 800	944 266	944 266	282 016	1 470 372	**3 993 720**
Vinnova	0	0	0	0	0	**0**
Sum	**352 800**	**2 832 266**	**2 127 266**	**1 432 016**	**2 964 372**	**9 708 720**
%	4%	29%	22%	15%	31%	100%
Inkind material budget/yr						
Project	**LEADERSHIP**	**ELEMENT**	**SURF**	**THERMAL**	**ITHZS**	**SUM**
Industry	0	1 083 333	183 333	583 333	600 000	**2 450 000**
Chalmers	0	486 000	486 000	486 000	1 446 000	**2 904 000**
Vinnova	0	0	0	0	0	**0**
Sum	**0**	**1 569 333**	**669 333**	**1 069 333**	**2 046 000**	**5 354 000**
%	0%	29%	13%	20%	38%	100%
Total budget/yr						
Project	**LEADERSHIP**	**ELEMENT**	**SURF**	**THERMAL**	**ITHZS**	**SUM**
Industry	0	4 663 000	2 316 000	2 875 000	2 994 000	12 848 000
Chalmers	652 800	1 430 266	1 430 266	768 016	2 916 372	7 197 720
Vinnova	1 000 000	1 500 000	1 500 000	1 500 000	1 500 000	7 000 000
Sum	**1 652 800**	**7 593 266**	**5 246 266**	**5 143 016**	**7 410 372**	**27 045 720**
%	6%	28%	19%	19%	27%	100%

7.5 *Spending budget*

The spending budget for GHz Centre is:

Spending budget GHz Centre 2017-2021	**2017**	**2018**	**2019**	**2020**	**2021**	**2017-2021**
Salaries at Chalmers (cash+inkind)	11 682 387	11 682 387	11 682 387	11 682 387	11 682 387	**58 411 934**
Material in kind at Chalmers	2 904 000	2 904 000	2 904 000	2 904 000	2 904 000	**14 520 000**
Cost SP involvement	200 000	200 000	200 000	200 000	200 000	**1 000 000**
Other direct costs incl travels	250 000	250 000	250 000	250 000	250 000	**1 250 000**
Indirect costs (OH)	3 844 333	3 844 333	3 844 333	3 844 333	3 844 333	**19 221 667**
Total cost Chalmers	**18 880 720**	**18 880 720**	**18 880 720**	**18 880 720**	**18 880 720**	**94 403 601**
Total cost in kind industry	8 165 000	8 165 000	8 165 000	8 165 000	8 165 000	**40 825 000**
Totala cost GHz Centre	**27 045 720**	**27 045 720**	**27 045 720**	**27 045 720**	**27 045 720**	**135 228 601**