Electronics R&D Roadmap

Top Sector HTSM

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1. Societal and economic relevance

1.1 Our role in society

The incredible flow of products from the Information, Communication and Consumer industries has changed our lives dramatically over the last 40 years. At the basis of these innovations is a continuous drive for smaller, better, cheaper and more efficient electronic components and circuits with increased functionalities[1]. The cost-effective scaling of integrated circuits (ICs) and the resulting exponential growth of chip complexity is named after scientist and Intel veteran Gordon Moore. Moore's law has generated a large number of innovations in the field of integrated circuits technology. The International Technology Roadmap for Semiconductors (ITRS)[2] and nowadays the Heterogeneous Integration Roadmap[3] refines the specific steps needed to fulfill the projected progress in IC technology. Innovations are required in fields like lithography, metrology, device physics, chemistry, materials, process technology, circuit design, EDA (Electronic Design Automation), embedded systems, etc.

Moore's law has sparked innovations in adjacent fields such as: displays, antenna, sensors, packaging techniques and energy sources. For a Dutch innovation roadmap, the developments are crucial in (1) the field of Moore's law, (2) the innovations in the neighboring fields often described as "More-than-Moore" including integrated sensor technologies and (3) the progress in various forms of packaging.
The progress in electronics development has created many high-tech innovative applications. The resulting volume production is described with overwhelming numbers: 1.5 billion mobile phones manufactured in 2017[4], the semiconductor industry reached a whopping 412 billion $ turnover in 2017 (+100% from 2009). Moreover, the Internet of Things developments will lead to tens of billions of connected devices. All of these innovations require improvements in analog and RF components, high-voltage devices, digital circuits, ultra-low power electronics, sensors and actuators, and skillful combinations of components into high-performance mixed-signal circuits.

Complementary to above economic perspective which creates more turn over, an excellent export position and more employment opportunities in our national ecosystem, societal challenges in the fields of energy and CO2 reduction, agriculture and food, health and care, climate and water, mobility and transport and a safe society require breakthroughs that only can be enabled by a new generation of electronic components and systems. Industry and knowledge institutes in the area of this Roadmap are well positioned to find a healthy balance with growth perspective to comply with both the economic and the societal challenges at the same time.

Electronics Roadmap – Scope

Electronics is pervasive in all aspects of society and daily life. The roadmap joins universities, international corporations, SME's and institutes around an innovation program that spreads from (chip) technology to component, to integrated circuits to electronic systems. Design, Characterization and test methodologies are included as well. The Electronics R&D Roadmap is enabling for many other HTSM Roadmaps and supports all of HTSM's Societal Themes.

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[1] High level group Key Enabling Technologies: Micro/nanotechnologies, November 2010. http://ec.europa.eu/enterprise/sectors/ict/files/kets/1_micro_and_nano_thematic_report_nov_15_final_final_en.pdf
[2] International Technology Roadmap for Semiconductors: www.itrs.net
[3] https://eps.ieee.org/technology/heterogeneous-integration-roadmap.html
[4] source: IDC Worldwide Quarterly Mobile Phone Tracker

1.2 Dutch perspective

The Netherlands is one of the most important European design and manufacturing countries for electronic components & circuits. Some of the world's major players in this field have major R&D activities here: Broadcom, Teledyne DALSA, Dialog, Maxim, NXP, Ampleon, Nexperia, Ericsson, STM, Synopsys, QUALCOMM, Thales Nederland, TI, Tyageo etc. Many Dutch SMEs operate at the forefront of application, design and technology. The production value represents a substantial portion of the total HTSM sector of 73 B€[5]. Dutch universities (TU Delft, TU Eindhoven and University of Twente) and knowledge institutes (ASTRON, CTIT, CWTe, DIMES, ESI, Holst Centre including IMEC-NL, MESA+, SRON, NIKHEF and TNO) rank amongst the most productive. The good position of Dutch industry is due to a long-lasting collaboration between industrial laboratories, research institutes and academia in the domains of technology, design, manufacturing and application. A large informal network allows the effective utilization of resources, resulting in joint product development, roadmaps and ecosystems around processing, circuit design, sensors and packaging.

This roadmap has the ambition to expand this position in the next decade and outlines the necessary research directions. Two perspectives are essential: technological development (both process and design technology) and applications' focus. The crossings of these axes yield the most promising implementations.

[5] https://www.hollandhightech.nl

2. Technology and Application challenges

2 .1 Technological development

The picture below depicts the two essential technology developments that underpin the Electronics Roadmap: Miniaturization through *More Moore* and Diversification through *More than Moore*. They are described in detail in sections 2.1.1. and 2.1.2.

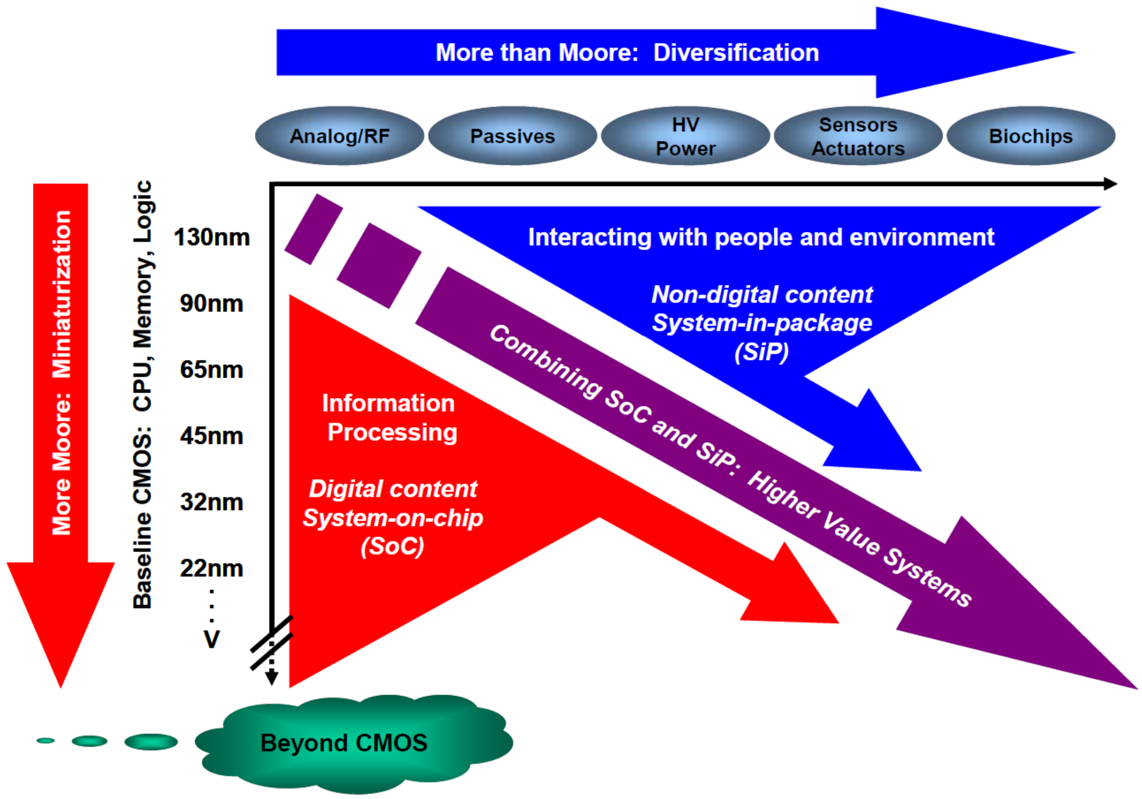

Fig. 1: The combined need for digital and non-digital functionalities in an integrated system is translated as a dual trend in the International Technology Roadmap for Semiconductors: miniaturization of the digital functions ("More Moore") and functional diversification ("More-than-Moore") [6]

2.1.1. More Moore

The main line of technology development under Moore's law is focused on digital CMOS scaling.
New hardware/software building blocks for advanced signal processing functions target mobile, IoT, Artificial Intelligence (AI) and automotive applications. The challenge is to deal with design complexity, product configurability and performance aspects (including power). This requires innovative hardware/software (multi-core) architectures in conjunction with new hardware/software verification technologies to master design complexity under stringent performance, energy and reliability constraints.
Advancements in technology push for growing integration of functions on a single die. Digital functions are extended with memories, input-output drivers, analog-to-digital interface, wireless interfaces and power management. Further functional integration will lead to system solutions with a minimum number of external components, thereby reducing the system cost and the energy consumption.

[6] "W. Arden, M. Brillouët, P. Cogez, M. Graef, et al., "More than Moore" White Paper, http://www.itrs.net/Links/2010ITRS/IRC-ITRSMtM- v2%203.pdf, fig.3

Extremely small dimensions and new materials (metal-gate, graphene, etc.) require design and model adaptations for every process node: new phenomena appear and old worries vanish. Slow degradation over life time, radiation hardness, reliability of components and the inherent variability require more attention. Future RF, analog and also digital design methodology will need to adapt to these new phenomena. Topics in the Dutch context: modeling of advanced devices and structures, incorporation in EDA tools, testing, advanced libraries and DSP architectures.
Downscaling and reliability demand circuit operation at (very) low voltages and power levels. New insights in circuit design, new technology options and the possibility to design intelligent analog and digital calibration mechanisms demand new system partitioning. Analog and RF components designed in scaled technologies can benefit from digitally-assisted and digitally-dominant design methodologies.
Dutch industry and academic research has an excellent reputation improving the performance of communication, radar, automotive and signal-processing circuits.

As the technological progress of advanced CMOS still continues, more advances in the neighboring "More-than-Moore" areas can be expected. Many "More-than-Moore" technologies exist because they enrich the circuits to a diversification available in CMOS technology.

2.1.2. More-than-Moore

Analog and RF

From the onset of the semiconductor industry, analog performance improvement has been very high on the agenda. Already for sixty years, scientists find ways to improve analog and RF functions. Where in the early days advances in performance were primarily connected to technology improvements (e.g. for low noise or high power), nowadays researchers use a highly creative toolbox and increasingly complex architectures to achieve the requirements set for future systems. Reconfigurability and multi-functional use are often additional requirements.

The Dutch innovation eco-system has a particular strength in analog and RF circuit design. The presence of academia, institutes, design houses, and manufacturing SME's and corporates is consistently leading to analog innovations with impact worldwide. Dutch companies were among the first to demonstrate fully integrated Bluetooth and Wifi products for instance. The innovations support a vast range of different functions and applications, notably precision sensor circuitry, advanced RF functions for communication, IoT, radar for the military, space and automotive use, (sub) mm-wave applications and power circuits for power conversion, RF power generation and drivers.

Many large companies, design houses and SME's recognize that despite the big words about digitization in today's society, analog design innovations are still essential. Already for decades, supply of analog and RF talent from universities is low compared to the demand of local industry. This has led to strong ecosystems of analog design companies clustering in Delft, Enschede and Eindhoven regions.

Sensors and actuators

Sensors and Micro-Electro-mechanical systems (MEMs) are often coined as the eyes, nose and ears of systems, such as mobile phones, cars, and robotics. Next to the omnipresent RF antennas and electronics, the list of potential usage models is close to infinite. Sensors and MEMS are applied in domains ranging from car-safety, water quality, chemical detection, security to specialized medical diagnosis. In the near future, sensors are expected to be embedded everywhere, in clothes or even on and in our own body and make everything "smarter". Smart sensors will be interconnected through the internet (Internet of Things), respond in real-time to dynamic and complex situations, while preserving control, system safety and reliability. These smart devices will become self-adaptive, robust, safe, and intuitive. The technology for micro actuators is a young and unexplored area with a large long-term potential. The leading position of Dutch academia, institutions and industry in this field is based on an excellent education, combined with a number of active pioneers in this field. Medium term topics are detectors for various gasses (Micro-Gas Chromatography to monitor nutrition quality or health care application), imaging technologies, and advanced patient monitoring systems. Radical new solutions are on the horizon, and their research will gradually lead to market introduction. Examples of such promising developments are lab-on-a-chip for low-cost chemical analyses (micro-fluidics, micro-membrane), THz non-destructive material analysis, the combinations of biological actuators and sensors, and the integration of photonic functions on CMOS.

High Voltage and Energy

Some domains of interaction between advanced CMOS and the physical world are less suited for integration. High-voltage and mains-connected applications, High Voltage battery systems for automotive and even lithium-based batteries for mobile phones, require technologies that can handle safely the supply voltages with the incidental overshoots. High-voltages, powers and currents can be handled in a huge range of applications using special structures (LDMOST) and technologies (BiCMOS, GaN, SiC).
Medium term research focuses on efficiency improvement of various energy conversion, transmission and storage. Dutch academic expertise is strong, and a fast-developing ecosystem of industry partners is building advanced solutions for instrumentation, renewable energy systems, car (fast) charging and more. Innovative power technologies like Gallium-Nitride (GaN) and Silicon-Carbide (SiC) is changing power switching and RF design, allowing for architectural changes. Large-scale investments enable more break-throughs in this field.

Large Area and Flexible Electronics

On the opposite side of the speed spectrum, reside the various activities in large-area and flexible electronics. Essential technology is comparable to large area printing techniques. The use of thin, plastic foils as a base substrate will ensure thinner and more flexible electronic products as compared to current glass-based and PCB-based electronics. Examples of future applications are: wearable medical devices such as skin patches and flexible X-ray imager sensors (biomedical), seamlessly integrated human machine touch interfaces (smart surfaces) and wireless NFC (near field communication) playing cards, disposable food and medication packages (internet-of-things). The focus on the research for the coming period is (i) to bring the already available process technologies and devices to a higher technology readiness level (TRL), (ii) realize functionally more complex (biomedical) devices, specifically on-the-body / in-the-body sensing technologies, that will require (iii) hybrid process development/combination of thin-film circuitry (transistor matrices and sensors) and traditional silicon technology on a single die, using (iv) ultimately fabrication processes such as additive printing techniques to drive down cost.

TeraHertz

Terahertz sensor technology has been identified as an important tool in the areas of safety, security, non-destructive inspection of materials, for instance in process control and medical diagnostics applications. The lower THz frequency band typically ranging from 100 GHz to 800 GHz are also interesting for high-speed short-distance communication applications. Research and development in this area will lead to communications systems with much higher data rates, better radar, high-resolution imaging that could penetrate smoke and fog, and better ways of identifying dangerous substances[7].
Many challenges need to be overcome to build sources and detectors in this region of the spectrum. Among the technological challenges that are mentioned, signal generation and detection in CMOS as well as III-V technologies or in hybrid electronic-photonic modules should be addressed. As priorities, affordable systems for imaging, spectroscopy and communication should be researched and developed as these will grow the application scope to many areas outside the laboratory walls.

[7] First Terahertz Amplifier "Goes to 11", IEEE Spectrum 4 Nov. 2014

Packaging and Antennas

Semiconductor chips and sub-assemblies require packaging, mounting on carriers, connections to displays, antennas, etc. Today ultra-thin packages are required for slim applications. New techniques are necessary to improve present day 2-dimensional and future 3-dimensional multi-die packaging (Through Silicon Vias, Through Polymer Vias), stress performance, and heat dissipation. For improvement of our environment, hazardous materials like lead in soldering of chips for power products, have to be replaced by new materials and processes. Silver- and Copper sintering processes seem to be promising alternatives, but have to be developed for the industry as "drop in technologies".
System-in-Packages (SiP) assemble various combinations of components. The addition of sensors and actuators pose an additional challenge on the packages as the sensor must be exposed to the external world without jeopardizing the remaining circuitry. The challenge of the interfacing for optical sensors calls for new packaging technologies/processes and materials to enable the required package specifications. Packaging costs for sensors and MEMs often form more than 50% of the component costs. A real cost break-through can be expected from techniques as film-assisted molding for MEMS, Flip chip, Bare die and exposed micro contacts, as well as from transfer- and injection- molding of wafers & large panels, by skipping the liquid underfill-, and post grinding or cleaning- processes. The importance of advanced packaging (chip integration or heterogeneous integration) is also confirmed by the fact that the traditional semiconductor industry's ITRS roadmap has been replaced by the Heterogeneous Integration roadmap.
The development and characterizing of new packaging materials for these techniques is a real challenge. This challenge requires co-development of new advanced packaging solutions, an activity that is supported by the Chip Integration Technology Centre (CITC) in the Netherlands. Testing of the individual components or the total SiP poses severe challenges due to limited accessibility.

Antennas are electromagnetic transducers. Wireless power transfer with antennas is a new field to charge capacitors and batteries. With silicon technology running at increasingly higher frequencies, the application range of antennas grows. Besides the traditional point-to-point arrangement, antenna arrays enable position-aware transmission and reception. Very high frequencies allow small antennas inside a package or on a die.

2.2 Supporting the Societal Themes

The inception of modern electronics enabled dramatic societal changes and unforeseen developments. Now that electronics has become ubiquitous and pervasive in all aspect of society, its profound contribution to society is often underestimated. In this paragraph we will highlight briefly how innovations in electronics contribute to Societal Themes as formulated in the HTSM Top Sector. Where appropriate, example projects are highlighted.

Health

Smart system developments and Internet of Things based services are advancing at an incredible rate and will have a profound effect on how we monitor and measure our health. This impact will be seen in new ways of observing and treating patients in our healthcare system, as well as in promoting vitality in a healthy aging society. The ITEA project PARTNER explores appropriate personalized care for chronic diseases.

Wearable wireless sensing systems can increasingly replace large costly hospital equipment, enabling continuous monitoring at home, giving doctors access to more complete medical grade data for diagnosis. Medical CE approved wireless systems to monitor brain and cardiac activity have even started to enter the hospitals themselves. Advances in low power circuit design are rapidly reducing the need for frequent charging. NANO4SPORTS (Interreg) ambitions to build innovative applications of health monitoring systems in sports optimization. The Plug and Play Design Centre (PPDC) initiative, located in Nijmegen, focusses on fast med-tech prototype development and testing in real-world medical setting.

Further miniaturization of components and systems makes it possible to embed the required sensing capabilities and systems for user interaction into objects in our daily environment. Such ubiquitous functionality, based on high tech systems, circumvents the issues typically seen with compliance related to the use of wearables. Even steps towards bioelectronics are made – bringing electronics on and in the human body.

Clearly, great strides need to be made in terms of end-to-end data security to build user trust. This can only be realized by building this in from the beginning at component, circuit and system level.

'Daring Applications & Innovations in Sensor Systems' (DAISY and DAISY2): disruptive sensor technology for everyone, an example of a regional private-public partnership program across several Societal Challenges (Agro-food, Water, Health & care, Safe Society)[8]

Sensors play an ever-increasing role in modern society: the increasing number of incidents with drones flying in the vicinity of airports is a good example of the necessity of high-performance sensor technology. Reliably detecting *and* classifying a large variety of objects in a complex environment requires very high-quality sensors. An Active Electronically Scanned Array (AESA) radar is the sensor of choice in the high-end security (defense) segment; however, the cost level of these sensors typically prohibits their use for other applications. DAISY realized a groundbreaking concept that makes high-end sensor technology accessible for mass applications in new application areas.

The main cost driver of the AESA sensor is the RF transmit/receive module. Daisy reduced this cost level through very high integration of the RF electronics using SiGe and GaAs semiconductor technologies: the complete module is integrated into a single component, comparable to a Lego brick. This results in a cost reduction of a factor of 10 compared to the current state of the art. Additionally, the volume of the sensor is reduced by a factor of 25, resulting in a thickness of only 2 cm. A step that can be compared to the transition from the bulky 'classical' television to a flat panel LCD TV. In the DAISY project this concept has been realized, resulting in a functioning demonstrator. Within the DAISY2 project this concept will be developed further, with explicit attention for cross-over applications of the underlying technologies, test and production methods.

Partners DAISY: Thales Nederland, NXP, TNO, HWM/WUR, University of Twente, RSC, Sencio, Noldus, TeraOptronics, Salland Engineering, Maser Engineering, Agritechnics
Partners DAISY2: Thales Nederland, NXP, TNO, WUR, Sencio, Noldus, Salland Engineering, Sintecs, VDM Kunststoftechniek, Etchform, FutureWater

[8] "Radar voor iedereen", New Scientist, december 2014.

Security

The Netherlands faces a number of complex security challenges in the coming decades that need innovations for the protection of national security interests. Enhanced electronic components and circuits are key enablers for affordable and societally acceptable defense and security systems. Access to such technologies is of strategic importance. Future challenges include a high degree of integration, massive and secure data handling, increased functionality, interconnectivity, configurability and resilient electronics. Challenges for a secure society are in the areas of digital security, operational security and physical security.

Strengthening **Digital security** asks for secure communications of the next generation requiring embedded authorization and authentication techniques. Dutch industry delivers integrated security solutions with the latest cryptographic techniques for a broad application range from connected cars to data centers, from healthcare to industrial control.

Sensor and data integration together with a capability to transform (sensor) data into user required information are crucial for **Operational security** to modernize the strength of a future-proof, adaptive armed forces[9]. This is particularly applicable in the maritime domain where new naval ships require advanced sensor technology. Dedicated Active Electronically Scanned Array antennas (AESA, also often referred to as phased-arrays) for radar systems, including custom RF, mixed-signal, digital assisted RF and digital electronics are an outstanding asset for the Dutch Navy, collaborating with Netherlands industry and research institutes to maintain and expand an excellent and renowned position worldwide in this area. Within this scope, STARS[10] was a PPS program running from 2010 – 2015 in which more than 70 researchers from Thales Nederland, NXP and TNO worked together with SME's and the Dutch technical universities to build up knowledge about reconfigurable sensor suites. End users of the technology were continuously involved. STARS led amongst others to more than 100 peer reviewed publications, and accepted world standard, and spill-over effects in other economic sectors like ICT and telecom.

Physical security covers the safety and security of people and objects in a broad sense against threats, including terrorism, organized crime and espionage. It entails wearable sensor and communication devices, virtual and augmented reality and the use of robotics to achieve an optimal division of tasks and cooperation between man and machine for the performance of defense and security tasks. Electronics at Terahertz frequencies enable the need to develop broadband sources and matrix detectors for detecting explosives and concealed weapons.

Platform Nederland Radarland, organizing the demand from the Societal Theme Security versus the industrial and technical solutions offered by HTSM Roadmaps (Security and Defense Systems, Electronics)[11]

[9] The memorandum "Houvast in een onzekere wereld - Lijnen van ontwikkeling in het meerjarig perspectief voor een duurzaam gerede en inzetbare krijgsmacht" was presented to the House of Representatives by the Minister of Defense on 14 February 2017 and outlines a multi-year perspective for the further strengthening of the armed forces: https://www.rijksoverheid.nl/documenten/rapporten/2017/02/14/meerjarig-perspectief-krijgsmacht-houvast-in-een-onzekere-wereld

[10] https://www.hollandhightech.nl/nationaal/actueel/nieuws/presentaties-holland-high-tech-roadmapevent-september-2015/security---pitch-3--stars

[11] https://www.defensie.nl/actueel/nieuws/2017/11/08/defensie-loopt-voorop-met-radar

The Netherlands has a leading knowledge infrastructure in the field of radar technology and development. Defense, industry and knowledge institutes work closely together on this. In order to foster cooperation in this area and to guarantee knowledge and technology development, the *Platform Nederland Radarland* was established on 30 May 2002. Founders are the Ministry of Defense, Thales Nederland, TNO, TU Delft and Ministry of Economic Affairs and Climate. The objectives are:
a. to combine and expand the knowledge of the parties as much as possible;
b. efficient coordination and synchronization of research and development efforts;
c. the initiation of adequate training.

The platform is aimed at fulfilling a joint long-term ambition and can only do so by focusing on research and technology development. An important tool is the preparation of roadmaps[12] in which this ambition is captured in coordinated and prioritized research programs and technology development projects. One of the major innovation areas of the Platform is in the area of RF front-end technology.

For example, within the scope of the Roadmap *Radar en Geïntegreerde Sensor suites 2010-2020,* more than 50 contracts with more than 100 partners have been carried out in the period 2010-2016.

Climate

Innovations for climate resilient cities, smart water services and systems that protect our delta will be abundantly equipped with sensor electronics, communicating wirelessly with datacenters. Our Electronics roadmap supports this with innovative solutions that may find their driver in other challenges but deliver a valuable solution regardless.

The Paris Agreement on climate change and the Dutch *Energie-agenda* call for a fundamental repositioning of our energy supply and drastic reduction in CO2 generation. Particularly the challenges on renewable energy generation and electric vehicles require electronics as a key enabler.
The transition to smart grid is dependent on a sound implementation of the smartness and flexibility in electricity streams through the network. Sensor and connectivity technology play an important role, and highly efficient power electronics is the essential ingredient to connect PV systems, wind turbines and electric vehicles to the smart grid.
Project DCSMART (ERA-NET H2020) explores DC distribution smart grids, among other things innovating in converters, modularity and algorithms. The project 3CCAR (ECSEL) ambitions to demonstrate next generation high reliability high efficiency power systems for electric vehicles.

Earth observation through satellites, drones and aircraft provides unique information with large scientific and practical use. The Dutch eco-system has strong competencies in the development of light weight and small scientific instruments, fit for airborne and space observation. A recent example is the development of the TROPOMI instrument, launched at the end of 2017 by ESA to measure atmospheric pollution with high spatial resolution. This mission, in the context of climate research, illustrates how electronic components can be integrated into an advanced satellite spectroscopic instrument. The miniaturization of the instrument through the development of immersed gratings and read-out electronics is a major breakthrough. Small satellites will increasingly be developed for climate or astrophysical research. They can be deployed as a distributed system, or as an interferometer, for

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[12] The most recent roadmap created within the Platform Nederland Radarland is *the Roadmap Radar en Geïntegreerde Sensorsuites 2030* and is approved by its Council on 20 September 2017. The roadmap can be made available on request.

instance in the high frequency (far-IR and THz) domain. It will require new developments in communication and detection technologies, especially at the level of electronic and photonic components. A fine example of the development, and integration of these technologies is the NWO funded program *Breakthroughs for interferometry technology in space*[13].

Mobility and Transport

The future of mobility and transport is dependent on innovations that facilitate transition to a clean and safe future, drastically reducing CO2, pollutants, casualties, traffic jams, noise and occupation of public space. The transition from combustion engine to electric drive is accelerating. Further electronic innovations in electric power handling in the vehicle as well as in the (fast) charging network will be key to providing economic solutions for mass adoption.

Autonomous driving is on the horizon as a major disruption of the traffic system. Both passenger as well as freight transport will be revolutionized by this development. The Netherlands is actively supporting trials with autonomous vehicles and is poised to become a large scale early adopter of this technology. It takes a broad range of advanced sensors like Radar, Lidar, Ultrasound, Camera and strong computational effort to achieve a functional safety-critical solution. With a strong ecosystem of institutes and industry, the Netherlands is strongly represented. Recently, the *ECO-TWINS* project demonstrated truck platooning in large scale trials. European project *ENSEMBLE* kicks off shortly, piloting multi-brand platooning across Europe.

EATA's project *CONCORDA* aims at enhancing and upgrading the environment for existing pilot projects for three main use cases: automated highway chauffeur, truck platooning and automated collision avoidance functionalities, while project *PRYSTINE* targets Fail-operational Urban Surround perceptION (FUSION), which is based on robust Radar and LiDAR sensor fusion, and control functions in order to enable safe automated driving in urban and rural environments.

Sustainable Economy

The societal need for a Dutch circular economy implies the industry to become more sustainable and foster sustainable economic growth. Innovation in electronics can contribute to the advent of a circular economy by increased awareness in the usage of materials, products and systems. Such awareness will lead to increased selectivity in the usage of material (like heavy metals) and reuse of raw materials that are now disposed as waste. Moreover, the industry wide transition from selling product to selling services implies the ownership of products to remain at the supplier's side for the full technical lifecycle. This transfer of ownership from user to producer results in increased interest from the supplier to provide products that can be reused and adhere to circular principles. Together with the trend of big data and IoT, electronics can support the matching of the useful with the technical lifetime. By monitoring the usage and performance during a use cycle, the need for maintenance, possibilities for up-grades to better suit the user's needs as well as the re-use potential for another use cycle can be determined. An inspiring example promoting sustainability and circular models in electronics is the Fairphone (https://www.fairphone.com/en/).

[13] http://www.stw.nl/nl/content/p17-27-bits-breakthroughs-interferometry-technology-space

TTW Perspectief program ZERO started recently, with the objective to research IoT solutions that do not require energy provision from batteries or the mains. See the sidebar for more information.

@ ZER0 Energy

ZERO: towards energy autonomous systems for Internet of Things

More and more, dyke sensors, street lights and surveillance cameras have a wireless internet connection. In the near future, we will see an explosive growth of Internet of Things (IoT). There is, however, one major problem: energy consumption. The common Lithium-Ion batteries will not be sufficient for delivering the energy to the expected 100 billion devices in 2025. The *TTW Perspectief* ZERO project aims to design energy autonomous IoT devices. They will have to produce twice as much energy, while at the same time consuming ten times less. For this, solar energy is an option, but also heat and vibration energy. New ways of energy storage will complete this, as well as methods of reducing energy needed for processing and wireless communications.

Partners: Altran, Dialog Semiconductor, Holst Centre, Nedap, NXP Semiconductors, Prodrive, Recore Systems, Resound, Sorama, Technolution, Thales, Topic, TU Eindhoven, TU Delft, University of Twente, Vinotion, Vodafone.

Innovations in Agriculture and Food are urgent, to feed a growing population in a sustainable and efficient manner. This is recognized by the initiation of the umbrella project HIGH TECH TO FEED THE WORLD. Electronics will play a key role in the many developments where sensing, data collection and control of environment are of the essence.

Horizon 2020 project INTERNET OF FARM AND FOOD 2020 has ambitious goals: to make precision farming a reality and to take a vital step towards a more sustainable food value chain. Through the Electronics systems and data processing, higher yields and higher quality produce are within reach.

Precision agriculture has great potential in the Dutch setting. Supporting technology may include wireless sensor networks, wireless communication, THz observation, drones equipped with among other things cameras and a suite of sensors. Experimentation with the new 5G wireless system is happening in the fieldlab 5GRONINGEN.

3. Priorities and implementation

3.1 Roadmap program

The ambitions of the HTSM-roadmap on Electronics have been captured in five themes that cover both the industrial research ambitions in this roadmap as well as the directions in which the academic education and research will develop. The themes are driven by the many needs of the applications that depend on the developments in Electronics. These requirements and applications have been described in the previous chapters.
The topics that are executed within the program on Electronics can be grouped in the following five themes.

Theme 1: Dealing with performance, variability, reliability, robustness and degradation in process technologies.

Every new process node or derivative requires adapting the circuits to the changing set of boundary conditions. With lower power supply, increased variability, and higher performance targets at lower energy consumption, often radical concept changes are needed. Due to the reducing margins in technology, reliability issues and (slow) degradation, achieving a good performance over the entire lifetime is not trivial. These problems are accelerated with aggressive voltage scaling all the way to the near threshold to improve the energy efficiency under limited performance conditions. The focus area is not confined to the More Moore technology only. Also More-than-Moore devices, like the integration of sensors in silicon, high voltage devices, or integration of passives will lead to additional, performance, reliability and robustness problems. Physics insight, new models and CAD tools and new circuit topologies and subsystem solutions (reconfigurable, low-power signal processors) are needed in communication domains, sensor interfaces and energy converters. The challenges are multi-disciplinary and require interaction between technology, circuits, architecture, and system.

Theme 1 partners: Dialog, NXP, Recore Systems, Salland Engineering, Synopsys, TNO, 4TU, Holst Centre, SystematIC, MESA+, DIMES

Theme 2: Electronics for radio communication and radar.

Communication systems connect the world. This application field will remain for decades one of the dominant system drivers for electronic components and circuits. Ranging from relatively low-performance but ultra-low energy sensor communication to high-performance radar systems, many novel applications and implementations are expected.
With cheaper components in smart packages, Ultra Low Power Networks (LAN, PAN, BAN, zero net power) equipped with sensors will enable the monitoring of parameters, going from body centric to large and complex infrastructures “Internet of Things”. An optimum integration in the network is required. The ultimate goal is to strive for net-zero power devices, where nodes in a network harvest their energy from the environment. Electronics for IoT is described in detail in Theme 3. A system-level power optimization approach by applying the broader concept of RF/analog/digital co-design will enable a mixed-signal design and/or heterogeneous design containing More-than-Moore components.
Co-operative networks and cognitive radios use the available bandwidth and are carrier-frequency adaptive. Especially in the lower frequency bands (< 5 GHz) traffic congestion can be avoided. On electronics level this requires broadband radio circuits. The traditional radio paradigm, from antenna, architecture and circuit design must be reinvented. The push towards higher bandwidths, accuracies and higher energy efficiencies in RF circuits, conversion topologies, drivers, power-amplifiers etc. is essential to enable this development.
The need for more bandwidth on one hand and the issues related to efficient spectrum management on the other hand will require very demanding specifications on analogue and mixed-signal circuits with respect to pulse shaping/modulation, robustness, resilience, re-configurability, frequency selectivity and linearity. Technology breakthroughs in these areas are necessary. Future 5G systems will open a mass market for millimeter-wave circuits and advanced beamforming architectures.

More and more high-frequency electronics are needed for the ever-increasing data throughput on a ubiquitous wireless infrastructure. 60GHz wireless systems have been developed, car radar electronics will be centered around 77 GHz, and Terahertz frequencies will be introduced. The THz frequency band has unique properties as spectroscopy of materials, imaging capabilities and an extremely high bandwidth for future communication systems. These unprecedented high frequency and high bandwidth systems are an enormous challenge for electronics and require new insights in working principles of new electronic devices working far beyond today's frequency limits. Applications range from astrophysical research to security. Sensors developed in the THz domain for professional applications (e.g. space) will penetrate in other application areas (security, health).
Active digitized arrays will steadily replace single receivers and transmitters. Individual users will receive their information through tailored, user-centered beams. Depending on the optimal partitioning of the system digitization will be performed on either the element level or on array level.

Theme 2 partners: ASTRON, Boschman, Bruco, CTIT, CWTe, Teledyne DALSA, Dialog, DIMES, Holst Centre, MESA+, NXP, Salland Engineering, SRON, ItoM, Qualcomm, Thales Nederland, TNO, 4TU, Ansem, Keysight, Ampleon

Theme 3: Smart circuitry for Internet of Things, home-, building- and industrial automation.

The world gets connected. By 2020 we may see a total of 50 billion devices connected to the internet. This accelerating development is summarized in the vision of the *Internet of Things* (IoT). The IoT landscape is diverse, ranging from personal area networks (PAN) to low power wide area networks (LPWA). The technologies will impact all aspects of society. Essential in this extremely important field is the combination of multiple functions to come to self-managed, cost-effective and durable solutions:

- Sensor functions ranging from air quality via presence detection to motion sensing. Sensors are the essential *eyes and ears* of the IoT system. Specific solutions often require today a More-than-Moore implementation, but a relentless drive will continue to push sensor systems to CMOS implementation for cost reasons and mass adoption.
- The implementation of smart algorithms enhances the sensor readings. Combination of data from multiple sensor modalities with advanced algorithmic approaches will allow for feature extraction in the sensor unit, reducing drastically the data rate transmitted by the sensor unit. Also the algorithmic processor must function at frugal power levels to fit the power budget of sensor nodes.
- Artificial Intelligence (AI) is rapidly becoming a corner stone of IoT systems. For optimal use of the data paths in the IoT network, part of the AI functionality must move from the cloud to the very edge of the cloud, also dubbed as the *fog*. The trend is emphasizing *edge nodes*, power and size constrained networking chips that combine all IoT functionality in a tiny chip.
- A connected world needs a high level of security in the solutions. For safety critical applications, security and user authentication is essential. Embodiment of secure elements in IoT solutions will provide a strong solution, combined with a secure operating system.
- Low power radios. Multiple standards are employed in parallel, and new standards will emerge over time. The innovation challenges are described in Theme 2.

Theme 3 partners: Dialog, Bruco, Eindhoven Energy Institute, Holst Centre, NXP, Teledyne DALSA, Systematic, TNO, 4TU, CTIT, CWTe, Ansem, Keysight, Sencio

Theme 4: Heterogeneous integration and packaging.

In chapter 2 we have described the trends in the domain of More-than-Moore technologies and packaging. As relevant topic in the roadmap Electronics they are core to Theme 4.
Additionally, valuable research is ongoing in the domain of low-cost electronics. Low-cost, high throughput technologies able to build transistors and sensors on large area flexible electronic foils are leaving the early research stage to enter the development of innovative products. The applications range from displays and

touch screens to cheap RF-IDs augmented with sensors. Cheap, mass-manufactured silicon-based sensors will play a dominant role in this field, providing the eyes, nose, and ears of tomorrow's sensor systems.
Ultimate heterogeneous integration trends appear in relation to e.g. manipulating fluidics (lab-on-a-chip for low-cost chemical analyses), the electronic pill (integrating biological actuators and sensors) and integration of photonic functions on CMOS.

Theme 4 partners: APC, Avantes, Bruco, Besi, Boschman, Holst Centre, NXP, Ampleon, Nexperia, Philips Lighting, 4TU, Prodrive, DIMES, MESA+, CWTe, CTIT, Ansem, Sencio, Trymax, Sempro, Liteq

Theme 5 Electronics for scientific instrumentation and for harsh conditions.

Advanced components and circuits with extreme performance levels allow building instruments that enable break-throughs in many scientific areas. The Netherlands has a strong position in several of these domains (material analysis, medical, robotics, microscopy, lithography, detectors for particle physics and space exploration).
This field produces vehicles to explore extreme operating conditions and are of significant value for industrial and scientific instruments.
The instrumentation and space challenges lie in the field of very low power and low noise circuitry, increased intelligence per pixel (per square micron), radiation hard electronics, and high speed (wireless) data transceivers. Further research is required on 3D integration & packaging, temperature stability and cooling for optimal integration of components in a final instrument.
For automotive (under the hood) and industrial applications, high temperature reliable operation is an important area of study. The harsh environment where these circuits operate, requires improved reliability, packaging and increased lifetime.

Theme 5 partners: ASTRON, Bruco, Nikhef, Panalytical, SRON, Systematic, NXP, Teledyne DALSA, Adimec. Sencio

3.2 European program

Europe requires major contributions from the electronics industry to tackle the Grand Challenges of the 21st century as outlined by the European Commission. Based on the technological progress anticipated in the near future, there are excellent opportunities to realize break-throughs that will benefit society.
The EU has put an effort in becoming self-sufficient on important critical areas of technology for high tech systems. The Netherlands has a strong position in several of these domains, from material analysis wireless communication, and medical instrumentation, to detectors for particle physics and space exploration.
With the "Horizon 2020" program as defined by the European Committee, collaborations on European level will enable a speedy execution of the themes as formulated above. Moreover, the organizations participating in Electronics research have a long history of participating successfully in European projects in programs as Eureka (Catrene/ITEA/PENTA) and Joint Technology Initiative ECSEL (ENIAC/Artemis/EPoSS). It is very relevant to continue on this line of engagement. Many if not all of the topics mentioned in this roadmap qualify for strategic partnerships with European organizations.
The EU is currently embarking on the 9th Framework Program (FP9[14]) that will cover the period 2021 – 2027. The ambition of the Electronics R&D Roadmap is to facilitate our Dutch stakeholders to play a major role in this 9th Framework Program to get the maximum out of it and actively pursue this ambition.

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4. Partners and process

The roadmap Electronics boasts an active network of academia partners, institutes and industry representatives. We've created an environment where partners meet in special workshops minimally three times a year, sharing the latest insights and preparing the future with thematic hot programs. Clear objective of the workshops is to facilitate the creation of connections and consortia for new business- and research-opportunities. We are keen to welcome new active participants to our workshops and our ecosystem, and are constantly searching for new developments. E.g., recently we covered the societal opportunities and electronics challenges of Quantum Computing (in the context of Qutech) and the upcoming 5G roll-out.

If you are interested in participating, please connect with us via electronics@hollandhightech.nl.

5. Investments:

Roadmap	**2015**	**2016**	**2017**	**2018**	**2019**
Industry	49.8	50.1	54.7	59.5	64.8
TNO	3.7	3.8	3.8	3.8	3.8
NLR	0	0	0	0	0
NWO	11.7	11.8	11.9	12	12
Universities	11.3	11.4	11.5	11.7	11.8
Departments and regions	4.9	4.9	5.5	6.1	6.8
Grand total	**81.4**	**82**	**87.4**	**93.1**	**99.2**

European agenda within roadmap	**2015**	**2016**	**2017**	**2018**	**2019**
Industry	24.2	24.4	28.6	33.2	38.1
TNO	4.3	4.4	4.7	5.1	5.5
NLR	0	0	0	0	0
NWO	0	0	0	0	0
Universities	0.2	0.2	0.9	1.7	2.8
Co-financing of European programs	5.2	5.2	6.2	7.2	8.4
European Commission	6.3	6.4	7.5	8.8	10.2

All figures in million € cash flow per year