European Core Technologies for future connectivity systems and components

Final COREnect Industry Roadmap

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LIST OF ABBREVIATIONS

5G	5th generation mobile communication
5G-ACIA	5G alliance for connected industries and automation
6G	6th generation mobile communication
AAU	Active antenna unit
ADAS	Advanced Driver Assistance Systems
ADC	Analogue to digital converter
AI	Artificial Intelligence
API	Application programming interface
ARM	Advanced RISC machine
ASIC	Application-specific integrated circuit
BiCMOS	Bipolar CMOS
BT	Bluetooth
CAPEX	Capital expenditures
CAPI	Common ISDN application programming interface
CCIX	Cache coherent interconnect
CMOS	Complementary metal oxide semiconductor
CPO	Co-Packaged Optics
CPU	Central processing unit
CU	Central unit
CXL	Compute express link
DAC	Digital to analogue converter
DBT	Dynamic binary translation
DBT	Dynamic binary translation
DC	Data center
DDR	Double data rate
DeMUX	Demultiplexer
DIMM	Dual inline memory module
DPU	Data processing unit
DSL	Domain-specific language
DSP	Digital signal processing
DU	Distributed unit
E/O	Electronics-to-optical
ECS	Electronic circuits and systems
ECU	Electronic control unit
EDA	Electronic design automation
eDRAM	Embedded dynamic random-access memory
EG	Expert group
EIRP	Effective isotopically radiated power
eMR	Electronic medical record
eNVM	Embedded non-volatile memory
FBAR	Film bulk acoustic resonator
FDSOI	Fully depleted silicon on insulator
FeRAM	Ferroelectric random-access memory
FinFET	Fin field-effect transistor
FPGA	Field programmable gate array
FTTH	Fiber to the home
FW	Firmware
GaN	Gallium nitride
GDPR	General data protection regulation
GPU	Graphical processing unit
h-BN	Hexagonal boron nitride
HBT	Heterojunction bipolar transistor
HEMT	High-electron-mobility transistor
HMI	Human-machine interface
HPC	High performance computing
HW	Hardware
I/O	Input /output
IC	Integrated circuit
IDM	Integrated device manufacturer
IIoT	Industrial internet of things
InP	Indium phosphide
IoT	Internet of things
IP	Intellectual property
IPR	Intellectual property rights
ISA	Instruction set architecture
ISG	Industry specification group
IWD	Intelligent wearable devices
JEDEC	Joint electron device engineering council
KPI	Key performance indicator
LDMOS	Planar double diffused MOSFET
LNA	Low noise amplifier
MCM	Multi-chip modules
MCU	Microcontroller unit
MIIT	Ministry of industry and information technology (China)
MIMO	Multiple input multiple output
ML	Machine learning
MLC	Multi-level cell
MPSOC	Multiprocessor system on a chip
MRAM	Magneto resistive random access memory
MUX	Multiplexer
NB-IoT	Narrowband IoT
NIC	Network interface card
NVM	Non-volatile memory
O/E	Optical-to-electronics
OEM	Original equipment manufacturer
OS	Operating system
OTA	Over the air
PA	Power amplifier
PC	Personal computer
PCB	Printed circuit board
PCI-SIG	Peripheral component interconnect special interest group
PCM	Phase-change memory
PCP	Programmable computing platforms
PON	Passive optical network
PUF	Physical unclonable function
QoS	Quality of service
R&I	Research and innovation
RADCOM	Radar and Communication
RAN	Radio access network
RF	Radio frequency
RFID	Radio-frequency identification
RISC	Reduced instruction set computer
ROW	Rest of the world
RTN	Random telegraph noise
RTO	Research and Technology Organisation
RU	Radio unit
SAW	Surface acoustic wave
SiGe	Silicon germanium
SiP	Systems-in-package
SME	Small and medium-sized enterprise
SoC	System on chip
SOI	Silicon on insulator
SRAM	Static random-access memory
SW	Software
SWOT	Strengths weaknesses opportunities threats
TRL	Technology readiness level
TSN	Time-sensitive networking
TSV	Through silicon via
UE	User Equipment
UI	User interface
URLLC	Ultra-reliable low latency communications
USA	United States of America
UV	Ultraviolet lithography
UWB	Ultra-wideband
V2V	Vehicle to vehicle
V2X	Vehicle to everything

EXECUTIVE SUMMARY

EUROPE'S PERSPECTIVE ON CONNECTIVITY

Amid geopolitical tension building up around the globe, as well as a pandemic that severely disrupted supply chains across the world, Europe is currently considering concrete actions to build a stronger position on digital technologies, to underpin Europe's sovereignty and industrial future. As the cradle of wireless and mobile communications, Europe has a strong position in connectivity infrastructure. It is currently the home of two of the three largest global equipment vendors, accounts for one third of the global market, and over one quarter of essential patents related to the 5G standard. In recent years, with rising competition from outside of Europe and increasing geopolitical interferences, Europe started to rethink and reevaluate its industry strategy, in order to maintain its leadership position in 5G and towards the development of 6G by 2030.

One of the rising concerns in this context is Europe's strong dependency on chipset vendors from outside of Europe, primarily US and Asia. Therefore, the domain of electronics components and chipsets for telecommunications is now attracting very strong industry and political interests, especially in areas where data, microelectronics and connectivity meet. Concrete steps have already been initiated in 2021, to start and overcome this challenge, and reinforce European strengths in microelectronics and in connectivity.

The European Chips Act, that provides the strategy of decades for Europe, laying out ambitious plan to regain global leadership in semiconductors, aims to reach 20% global chip market share for Europe by 2030. An Important Project of Common European Interest (IPCEI) on Microelectronics and Communications is being set up, and Joint Undertakings in Key Digital Technology and Smart Networks and Services have been launched.

Developed between 2020 and 2022, with the participation of 100+ technical experts from 50+ organisations across Europe, the COREnect[1] strategic R&I roadmap provides detailed insights on strategic actions required to achieve European leadership in microelectronics and connectivity within the next 10 years, towards the development of 6G, supporting Europe's twin transition towards a green and digital future.

1 COREnect is a 2-year Horizon 2020 Coordination and Support Action project, bringing together 12 major European industry and R&D leaders from both the microelectronics and telecommunications sectors. They have jointly defined and proposed a strategic R&I roadmap to achieve European leadership in microelectronics and connectivity within the next decades. The project started in July 2020 and will be completed by June 2022.

STRATEGIC TRENDS AND OPPORTUNITIES FOR MICROELECTRONICS AND FUTURE CONNECTIVITY

European challenges and opportunities on microelectronics and future connectivity can be summarised as follows:

Opportunities

Strong global position on wireless and wireline infrastructure markets and R&D, and strategic link between core semiconductor technology capability and key verticals (automotive, industrial, space and defence…). Combining those two assets makes Europe a strong contender to take a leading role towards 6G and beyond, while covering the entire value chain.

Europe has strong research in heterogeneous integration for many applications (high-performance computing, photonics, RF). In the industrial data market, that is several orders of magnitude bigger than the personal data market, Europe should not leave the storage and handling of these data (both 'central' and 'edge') to non-European companies.

Challenges

Digitalisation modifies the European value chain, in which Europe risks to reduce its technological sovereignty. The rise of AI and radio access network (RAN)-virtualisation, for example, is likely to increase our dependency on USA technologies for supplying, e.g., digital logic and processors.

Geopolitical tensions and trade restrictions impose an increased risk of disruption of the European supply chain. It is key for Europe to mitigate this risk through a more diverse and resilient supply chain.

CORENECT STRATEGIC R&I ROADMAP

COREnect proposes a multi-stakeholder strategic R&I roadmap with a 10- to 15-year timeline, for Europe to address future connectivity technologies with a value-chain approach. The roadmap addresses different timeframes with a changing focus in terms of strategic investments, markets, and technological development in three strategic focus areas. 'Compute and store' investigates the role of computing and storage solutions for Europe's 5G and 6G sovereignty. 'Connect and communicate' looks at Radio Access Networks (RAN), consumer grade connectivity, industrial grade connectivity, and data centres. Finally, 'Sense and power' focuses on the areas of sensing and power for future network.

SUMMARY OF CORENECT R&I ROADMAP RECOMMENDATIONS, FROM THE THREE STRATEGIC FOCUS AREAS

#	SHORT TERM (<2026)
Rc.s.1	Maintain & strengthen Europe position on semiconductor manufacturing equipment
Rc.s.2	Strengthen Europe's position on mature technologies
Rc.s.3	Strengthen Europe's position on EDA solution market
Rc.s.4	Support the development of open hardware and software ecosystem
Rc.s.5	Support the development of components/HW technologies catering needs of connectivity markets
Rc.s.6	Support the development of platform chipsets enabling a wide range of applications on a single modem
Rc.s.7	Improve EU technical university attractivity and admissibility to increase the pool of talents available in EU
Rc.s.8	Create acceptance for sensitive data sharing
	MID-TERM (2026 - 2030)
Rc.m.1	Increase IC design capabilities in digital and analogue to ensure a sufficiently large pool of resources in EU
Rc.m.2	Develop heterogeneous integration technologies (2.5D/3D) in the EU to address complexity and performances challenges in an innovative way leveraging EU mature technology strength
Rc.m.3	Establish a European fabless ecosystem developing complex SOC achieved in leading edge CMOS technologies to serve the domestic and international market
Rc.m.4	Deploy open hardware and software ecosystems targeting safety and security contexts
Rc.m.5	Establish leading edge technology source in Europe
	LONG TERM (> 2030)
Rc.l.1	Enable the development of next generation derivative technologies to secure Europe leadership in the long term
Rc.l.2	Enable European Cloud solution & service providers to address domestic and international markets
Rc.l.3	Strengthen leading edge technology source in Europe

In addition to the above, recommendations related to R&I investment requirements, as well as recommendations for strategic political support, are also part of the COREnect R&I roadmap.

SUMMARY OF HIGH-LEVEL RECOMMENDATIONS ON R&I INVESTMENT REQUIREMENTS

Rh.1	Create and strengthen concrete actions for market growth through technological excellence to build economic sustainable sovereignty and resilience
Rh.2	Control strategically over several critical and/or strategic parts of the value chains and build up value networks instead of value chains
Rh.3	Streamline further strategic priorities between Europe, Member States and Industry including the definition of top-priority ambitions
Rh.4	Enhance eco-systems of large enterprises, SME's and RTO's both in horizontal competence areas as in vertical value chains
Rh.5	Improve further the efficiency of the process and administration of European research programme
Rh.6	Recommend a dedicated call for a strategic call on micro-electronics for 6G with all involved key stakeholders in Europe within the KDT framework
Rh.7	Promote the role SMEs in the European microelectronics and connectivity ecosystem
Rh.8	Create conditions for the emerge of one or more European champion(s) from microelectronics and connectivity domains

SUMMARY OF HIGH-LEVEL RECOMMENDATIONS ON STRATEGIC ACTIONS FOR POLITICAL SUPPORT

Rh.9	Speed up 5G deployment in Europe and define a consistent EU spectrum policy
Rh.10	Support Europe's contribution to standardisation activities
Rh.11	Secure access to leading edge CMOS technologies
Rh.12	Take measure to boost the European micro-electronics community
Rh.13	Adapt policy to geopolitical tension
Rh.14	Define and enforce new regulation aligned with European values and ethical principles on privacy, security and sustainability
Rh.15	Strategic Infrastructure programme led by Member States and the Commission

CONCLUSION AND NEXT STEPS

With this roadmap in hands, a new journey may begin, to truly realise and deliver the common vision of telecommunications and microelectronics industries, aiming at building a strong European position in those key digital technologies. Facing great uncertainties ahead in globalisation, geopolitics, post-pandemic economy and climate change, the road towards 6G and European digital sovereignty will be extremely challenging. The COREnect consortium may only wish this roadmap to provide food for thoughts, but more importantly a light, a compass, a map, and an action plan for Europe and all the related private and public stakeholders, to find their way and succeed in this journey.

CONTENT

01 INTRODUCTION

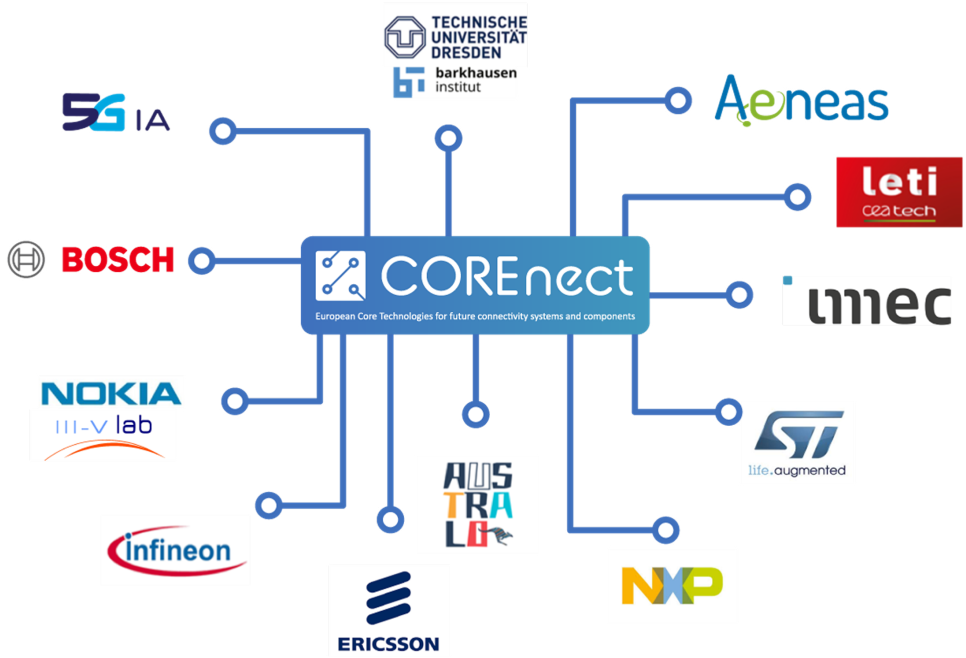


Figure 1 An overview of COREnect Consortium

COREnect (European Core Technologies for future connectivity systems and components) is a 2-year Coordination and Support Action project selected by the European Commission in the frame of the Horizon 2020 Research & Innovation programme, that has started its activities since the 1st of July 2020. One of the key COREnect objectives is to bring European industry and R&D leaders from both the microelectronics and telecommunications sectors together as depicted in Figure 1, jointly defining a strategic R&I roadmap for 5G/6G microelectronics and future connectivity, supporting the objectives of Europe's strategic autonomy and sovereignty.

To facilitate the roadmapping work, three (3) expert groups were established in October 2020 with more than 100 contributing technical experts from both COREnect partners, as well as 40 external organisations, representing the microelectronics and telecommunications value chain[2]. These 3 expert groups were organised into 3 strategic focus areas that are critical for addressing microelectronics needs to support future connectivity:

- Expert Group #1: Compute & Store
- Expert Group #2: Connect & Communicate
- Expert Group #3: Sense & Power

2 Cf. acknowledgement in Annex A

The timeline and the three phases of this work are illustrated in Figure 2. Roadmap directions were defined and first input ("raw data") was captured during the first phase; then the roadmap data was further processed, refined, and enriched, and a common approach and structure was introduced across the different expert groups during the second phase. During the third phase, a common and consolidated roadmap proposition was developed, based on the material gathered during the preceding phases, i.e., D3.3 Initial COREnect industry roadmap and D3.4 Intermediate COREnect roadmap, leading to this document entitled D3.6 Final COREnect industry roadmap. A vision of future connectivity system in 2030 and beyond, i.e. 6th Generation (6G) network, is also briefly described with insights collected from the EU 6G Flagship project Hexa-X, setting the scene for this final roadmap.

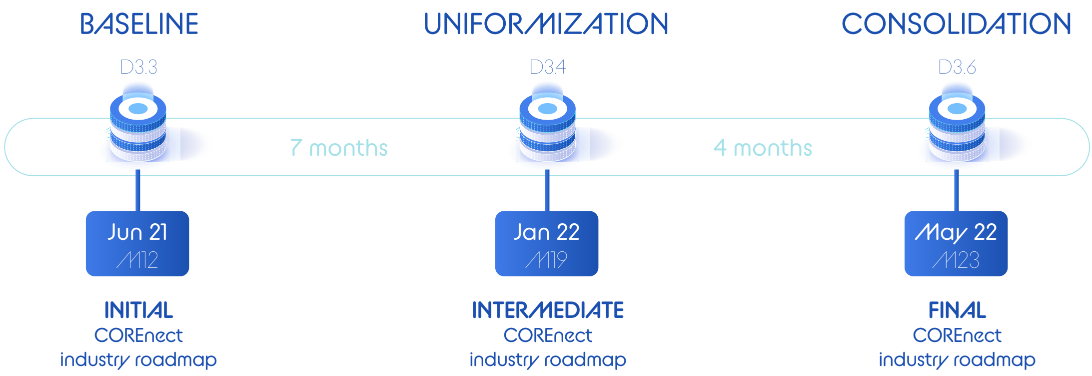


Figure 2 COREnect roadmap building timeline

The structure of this deliverable is as follows. Sections 2 sets the scene on Europe's current and future perspective on connectivity. Section 3 provides an overview of the strategic trends and potential business opportunities in the areas of future connectivity and microelectronics. Section 4 then carries the main part of the strategic R&I roadmap, where SWOT analyses on different market segments, as well as identified strategic actions for the three strategic focus areas are discussed, based on comprehensive interactions within and among the tree expert groups. Finally, section 5 draws the main conclusions.

Note

The COREnect roadmap is composed of three documents. Deliverable 3.6 "Final COREnect Industry Roadmap" is the main document, describing the proposed roadmap and providing a summary of all recommendations. Deliverables 3.7 "Core Technologies Development Recommendations and Guidelines" and 2.2 "Consolidated vision and requirement report" are companion documents to the roadmap. D3.7 provides a synthesis of the industry roadmap and a list of recommendations, guidelines and action proposals, while D2.2 focuses on the investments required to build a stronger European sovereignty in microelectronics and connectivity.

02 EUROPE'S PERSPECTIVE ON CONNECTIVITY

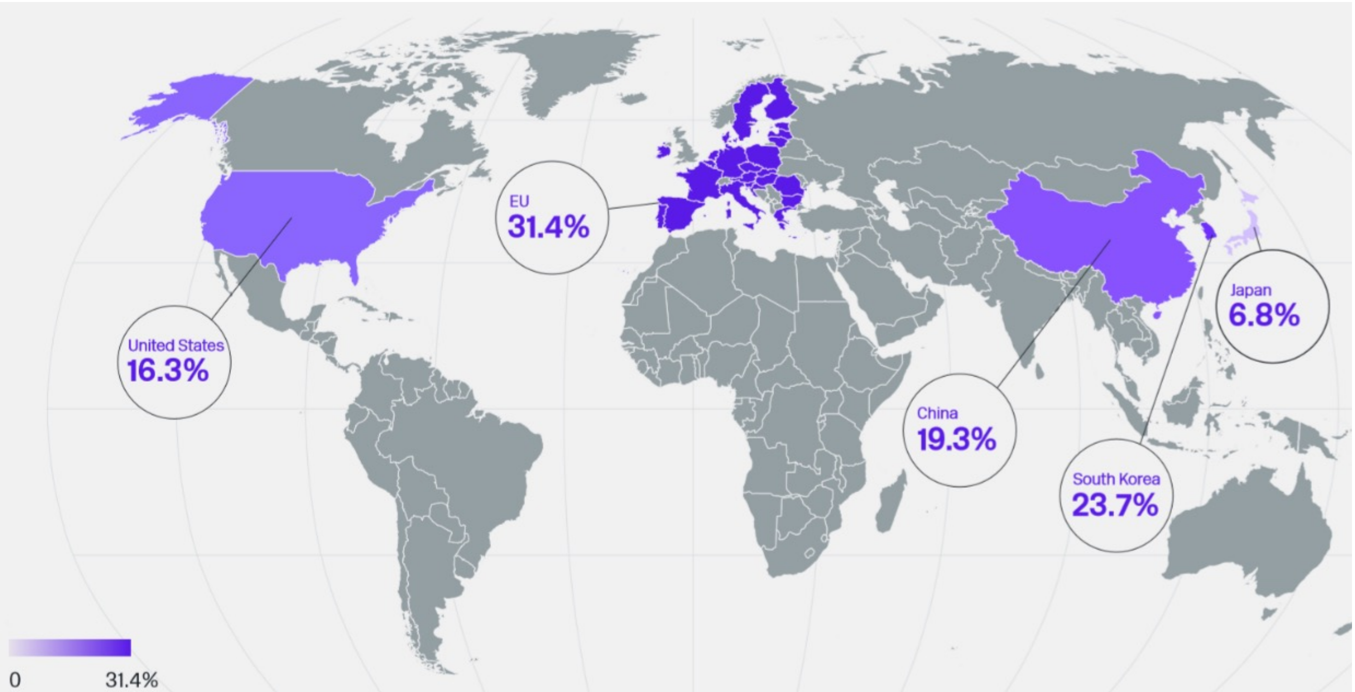


Figure 3 Essential 5G patents mapped to regions as of March 2020[4]

2.1 CURRENT POSITION

As demonstrated during the pandemic, even more than ever before, connectivity has become the backbone of our society and economy. The critical infrastructures of the 21st century not only connect people and places, but also shape values and norms, infuse innovations and businesses, and enable growth and green transition. As exemplified by the rising geopolitical tensions, with gigantic amount of personal and industry data flowing within the network, connectivity infrastructure is and will continue to be a central piece of sovereignty and security of countries and regions. Those who controls the connectivity solutions of today and tomorrow, such as 5G and 6G, will gain great advantages with respect to economic, societal and political outcomes.

As the cradle of wireless and mobile communications, Europe has a strong position in connectivity infrastructure. It is currently the home of two of the three largest global equipment vendors, i.e., Ericsson and Nokia, that account for around one third of the $383.86 billion global market and over one quarter of essential patents related to the 5G standard as of 2019 as shown in Figure 3[3]. Historically it has taken roughly ten years to ramp up the new generation from early research into commercialisation.

3. www.twobirds.com/-/media/pdfs/news/articles/2019/determining-which-companies-are-leading-the-5g-race.pdf
4. www.twobirds.com/en/insights/2020/global/who-is-leading-5g-development-2020-update

In recent years, with rising competition from outside of Europe and increasing geopolitical interferences, Europe started to rethink and re-evaluate its industry strategy, in order to maintain its leadership position in 5G and towards the development of 6G. One of the rising concerns in this context is Europe's strong dependency on chipset vendors from outside of Europe, primarily US and Asia. Today, the European microelectronics industry is delivering microelectronic components to global device original equipment manufacturer (OEM) and accounts for 4% of the out of 408$ billion telecommunications production market[5]. It is in a much more vulnerable position than the US, China, or Taiwan, in terms of the capability to obtain a full system solution, including processors, modems, and high frequency radio modules. Consequently, Europe has little control on the security of the supply chain. The potential threat of including compromised components and chipsets in critical infrastructures could severely harm the integrity of such infrastructures.

It has therefore become an urgent matter to address this problem, from both the economic perspective and from the technological autonomy standpoint. Concrete steps have already been initiated to overcome this challenge and reinforce European strengths in microelectronics and in connectivity, e.g., with the launch of Important Project of Common European Interest (IPCEI) on Microelectronics and Communications[6], and the Key Digital Technology (KDT)[7] and Smart Networks and Services (SNS) Joint Undertakings[8]. In addition, the European Chips Act, published by the European Commission in February 2022, is laying out ambitious plan to regain global leadership in semiconductors[9]. To reach its ambition of 20% global chip market share in 2030, Europe must regain and master chip design and manufacturing capability in the connectivity domain (5G/6G), that accounts for around 1/3 of the global chip market to date, and moreover is critical for strengthening the European digital sovereignty.

The COREnect strategic R&I roadmap detailed in this report provides detailed insights on strategic actions required to achieve European leadership in microelectronics and connectivity within the next 10 years, towards the development of 6G thus, supporting Europe's twin transition towards a green and digital future.

2.2 PROSPECTS TOWARDS 2030 AND BEYOND

Currently, the development of 6G technologies is still in its infancy. Despite many uncertainties and opportunities in the horizon, it is possible to outline a pathway of what will be required from a 6G system. As envisioned in[10,11], 6G will further evolve 5G networks and the supported services. Connectivity in the 6G era will further push digitalisation by allowing real-time connectivity among the physical, digital and human worlds, while relying on their digital twin representation or virtual world, and meanwhile address societal considerations related to sustainability, trustworthiness and digital inclusion. It will drive a large scale and complete adoption of uses cases defined during the 5G design phase, with significantly decreased deployment and operation costs. It will also enable new and innovative use-case-driven solutions, with higher economic and societal values, as depicted in Figure 4.

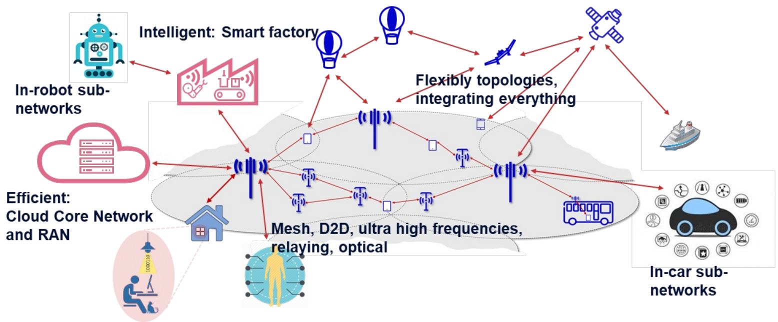


Figure 4 A first view of 6G network developed by EU 6G Flagship Project Hexa-X[12]

5 https://ec.europa.eu/digital-single-market/en/news/emerging-technologies-electronic-components-and-systems-ecs-opportunities-ahead-0
6 https://www.ipcei-me.eu/
7 https://www.kdt-ju.europa.eu/
8 https://digital-strategy.ec.europa.eu/en/policies/smart-networks-and-services-joint-undertaking
9 https://ec.europa.eu/commission/presscorner/detail/en/ip_22_729
10 https://5g-ppp.eu/wp-content/uploads/2021/06/WhitePaper-6G-Europe.pdf
11 https://ieeexplore.ieee.org/document/9625032
12 https://hexa-x.eu/wp-content/uploads/2022/03/Hexa-X_D5.1_full_version_v1.1.pdf

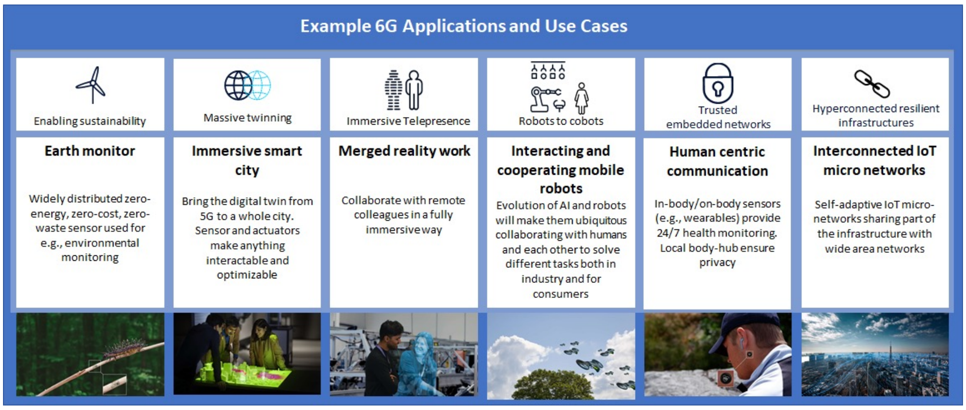


Figure 5 Examples of 6G Applications and Use cases

As projected in[13], connectivity encompassing 5G/6G is in the trajectory of triggering $13.2 trillion global sales across ICT industry sectors by 2035, representing 5% of global real GDP, while the 5G/6G value chain shall be able to generate 22.3 million jobs globally by 2035[14]. This estimation does not include the impact of connectivity on non-ICT sectors, e.g., agriculture, manufacturing, public services, transport and storage, and wholesale/retail sales, which may potentially create much higher economic values than the ICT sectors themselves and create great growth opportunities for both big industries and SMEs. In addition to creating economic values, there is a clear and strong consensus within the European telecommunications industry: future connectivity solution such as 6G shall fully support and further accelerate green and digital twin transition of society and economy, increasing the efficiency in the use of resources and facilitating new and sustainable ways of living. A few examples of 6G applications and use cases that could deliver high societal and economic values in 2030 are illustrated in Figure 5 based on early study carried out in[15].

Based on 6G vision in[16], the current expectations are for 6G to address both performance as well as value-drive goals:

Performance-driven design goals

- **Connecting intelligence:** to enable the automation of network operation and management for improved efficiency and reduce cost with artificial intelligence (AI), and support the connection of a multitude of autonomous devices including robots and automated environment by enabling reliable and secure interconnection and communications among intelligent machines/robots.

- **Extreme performance:** to unlock commercial values of new technologies at sub-THz frequency range and provide bit rates in the order of hundreds of Gigabits per second to a few terabits per second, extremely low (imperceptible) latencies, seemingly infinite capacity, precision localisation and sensing, pushing the performance beyond what is possible with 5G with reasonable low cost and energy consumption.

- **Network of Networks:** to enable flexible operation and topologies as well as efficient management of various access networks, and support network as well as device programmability, where deployments and operations can easily be customised to address the specific industry needs with reduced cost.

Value-driven design goals

- **Sustainability:** to empower environmental, social and economic resilience and sustainability, reducing energy consumption and CO_2 footprint of ICT industry and connectivity-enabled industry sectors other than ICT, and addressing United Nations (UN) Sustainability Development Goals (SDG) that are significantly benefiting from connectivity such as SDG[17].

- **Trustworthiness:** to fulfil the requirements of digital critical infrastructure and connected heterogeneous devices on resilience, privacy, security, dependability (reliability and integrity) and safety, and provide adaptable and verifiable trustworthiness to support real-time data flow among digital, physical and human worlds.

13 https://www.raconteur.net/infographics/the-economic-impact-of-5g/
14 https://www.raconteur.net/infographics/the-economic-impact-of-5g/
15 https://hexa-x.eu/wp-content/uploads/2021/05/Hexa-X_D1.2.pdf
16 https://hexa-x.eu/wp-content/uploads/2022/04/Hexa-X_D1.2_Edited.pdf
17 https://www.gsma.com/betterfuture/2020sdgimpactreport/wpcontent/uploads/2020/09/2020-Mobile-Industry-Impact-ReportSDGs.pdf?utm_source=better_future_site&utm_medium=search_engine&utm_campaign=2020_SDG_impact_report

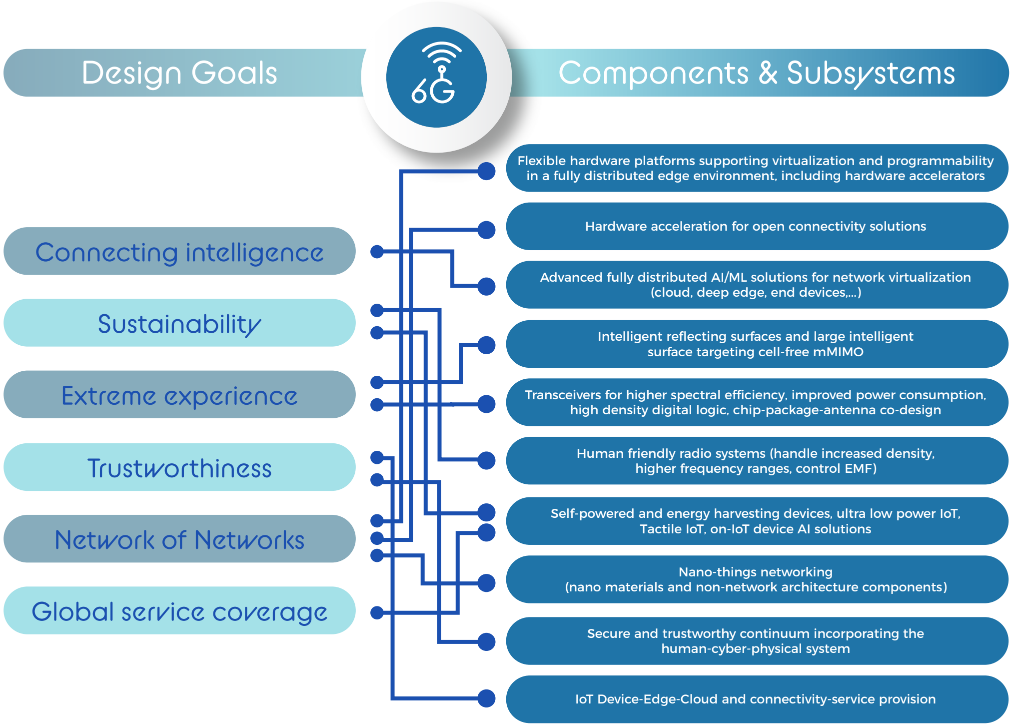


Figure 6 Indicative mapping of 6G goals with components and subsystems

Global coverage: to support efficient and affordable solutions for global service coverage, connecting remote places, enabling new services and businesses that will promote economic growth and reduce the digital divide as well as improving safety and operation efficiency in those currently under-/uncovered areas. It is one of the major enablers for addressing most UN SDGs by providing digital opportunities for the underserved population.

From a technological perspective, the telecommunications market has traditionally been considered highly important for the microelectronics sector, keeping on pushing the technology envelope aggressively. To achieve the above performance-driven and value-driven design goals, 6G, among other digital technologies, will depend on breakthroughs offered by the microelectronics sector. New design requirements and approaches, new types of components, devices and chipset solutions and even new ecosystems will emerge, leading to new business opportunities and even disruptions in the microelectronics and connectivity markets. An indicative map linking 6G design goals and 6G components and subsystems related to microelectronics is shown in Figure 6. It is based on the first analysis of topics considered in the SNS Phase 1 R&I Work Programme (WP)[18], providing a bird's-eye view on the interactions between future connectivity and microelectronics from a network perspective.

One of the most important aspects in the telecommunications sector is the evolution and allocation of spectrum towards 6G. This will impose a major impact on setting requirements for 6G components and subsystems. In general, 6G spectrum deployment is expected to adopt a similar approach as the one being used for 5G spectrum deployment[19,20], where mid-band spectrum (5.9 GHz – 7.1 GHz) would be allocated in the large-scale deployment for offering wide bandwidth at higher frequency than 5G and upper mm-wave (100 – 300 GHz) would be allocated in local deployment for achieving even higher data rates. Developing radio components, subsystems and commercial offers that operate at those bands will be crucial and create new business opportunities in the microelectronics market.

Currently, there is also a rising trend on network disaggregation leading to the Open Radio Access Network (RAN) concept, which enables mobile network operators to use equipment from multiple vendors and still ensure interoperability. However as analysed in[21,22], the development of Open RAN is still in an early phase and cybersecurity remains a significant challenge. From European strategy perspective, it has the potential to open telecom market, foster competitions and create new business opportunities but could also lead to new or increased critical dependencies of Europe to other continents, e.g., in the area of components and cloud. Its implication and impact on European connectivity and microelectronics industry remain to be seen.

The next sections show how the microelectronics industry may address the design goals of future connectivity systems. Strategic trends, opportunities and R&I roadmap are presented in detail, based on joint studies by industry, research and technology organisation (RTO) and academia experts, from both the microelectronics and connectivity domains, with a value chain approach.

18 https://digital-strategy.ec.europa.eu/en/policies/sns-work-programme
19 https://www.itu.int/en/ITU R/study-groups/rcpm/Pages/wrc 23 studies.aspx
20 Janette Stewart and Chris Nickerson, Investigation into spectrum for 6G key findings from a study for Qualcomm, https://www.techuk.org
21 https://ec.europa.eu/commission/presscorner/detail/en/IP_22_2881
22 https://www.bsi.bund.de/SharedDocs/Downloads/EN/BSI/Publications/Studies/5G/5GRAN-Risk-Analysis.pdf?__blob=publicationFile&v=5

03 STRATEGIC TRENDS AND OPPORTUNITIES FOR MICROELECTRONICS AND FUTURE CONNECTIVITY

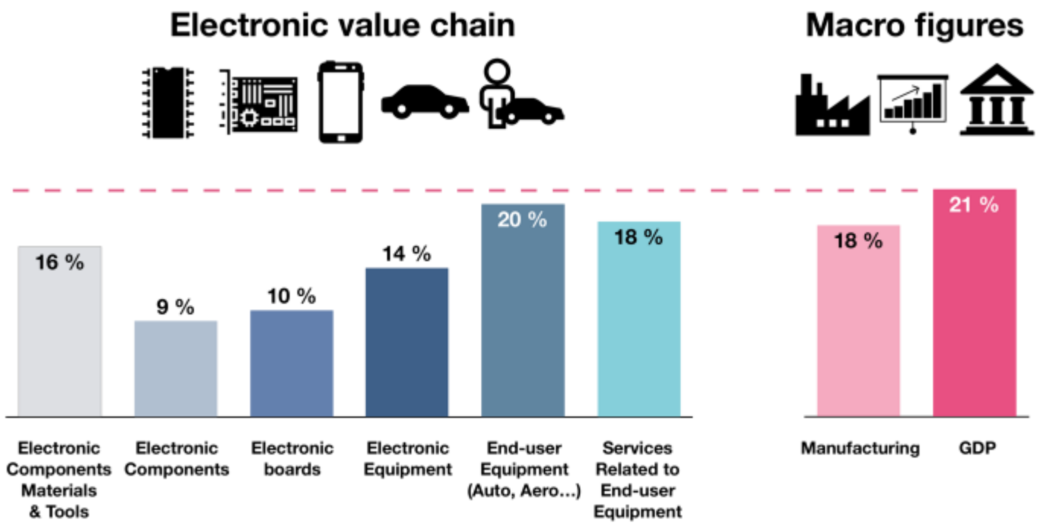


Figure 7 European share of the world production of the global electronic value chain[23]

3.1 MAJOR TRENDS AND POSITION OF EUROPE

To identify Europe's major challenges and opportunities when it comes to components for connectivity technology, the first step is to review Europe's position in the overall value chain. As illustrated in Figure 7, Europe still holds a good share in materials and tools to produce electronic components. Europe's production share is, however, lower at levels such as electronic equipment, electronic boards, and electronic components.

In Europe, the leading end-user segments are industrial electronics, aerospace defence and security, and automotive electronics. In the global electronics ecosystem, the leading segments are still the consumer mass markets (mobile phones, PCs). Consequently, Europe's share in the world production is also highest in those segments where Europe is strongest, as illustrated in Figure 8.

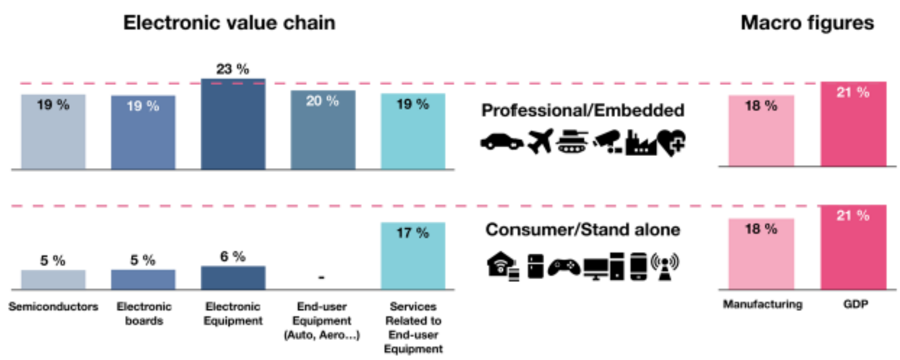


Figure 8 European share of the world production of the global electronic market focusing on professional/embedded and consumer electronic value chains[23]

23 www.decision.eu/wp-content/uploads/2020/02/DECISION_Study_Electronics_Ecosystem.pdf

While Europe is producing 9% of the overall electronic components (see Figure 7), its market share is 19% on the market it serves today as shown in Figure 8 (professional and embedded segments, the wireless infrastructure market being a good example with Ericsson and Nokia). These figures are in line with Europe's GDP. Since Europe hardly addresses the consumer market, the European ecosystem requires a moderated manufacturing capacity mainly focused on mature and derivate technologies. For example: automotive represents today only about 10%[24], but this is expected to increase in the coming years. The installed European semiconductor manufacturing capability to address Europe's key verticals is sized accordingly. As illustrated in Figure 9, Europe has a strong presence on 200 mm facilities, with STMicroelectronics and Infineon among the top 5 global leaders. This is in line with the technologies required by the European ecosystems and value chain.

The situation on 300 mm wafers manufacturing is completely different. On 300 mm, there is no European actor among the top 10 players. This is directly correlated with the European position on the market since the top 300 mm manufacturing players are addressing either memory (Samsung, Micron, SK Hynix, Kioxia) or advanced logic (Samsung, TSMC, Intel). These are two areas where Europe is hardly represented. As illustrated in Figure 10, the installed manufacturing capability of a given region directly correlates with the technology nodes required by the targeted markets of the associated value chain and ecosystem.

China, Japan, USA, and Korea have most of their installed capacity for technology ranging from > 10 nm to < 20 nm, which serves their memory production. 75% of Europe's installed capacity supports > 40 nm (50% for technologies > 180 nm) which serves its key verticals (automotive, industrial, health, ...). Taiwan has a more balanced situation because TSMC's foundry business model clearly focusses on the most advanced nodes. TSMC's 1Q21 revenue, depicted in Figure 11, shows that the smaller nodes are driven by the smartphone and HPC business.

(Ranked by Share of Total WW Monthly Installed Capacity)

300mm Wafers: WW Share	300mm Wafers: Top 10 in Capacity	200mm Wafers: WW Share	200mm Wafers: Top 10 in Capacity	≤150mm Wafers: WW Share	≤150mm Wafers: Top 10 in Capacity
21%	Samsung	10%	TSMC	9%	CR Micro
15%	TSMC	6%	STMicro	8%	Silan
14%	Micron	6%	UMC	8%	Nuvoton
13%	SK Hynix	6%	Infineon	7%	ON Semi
11%	Kioxia/WD	6%	TI	5%	STMicro
6%	Intel	5%	SMIC	4%	TI
4%	GlobalFoundries	4%	Vanguard	3%	Rohm + Lapis
3%	UMC	4%	NXP	3%	Toshiba
2%	Powerchip	4%	ON Semi	3%	Diodes
2%	TI	3%	Toshiba	3%	TSMC

WW Share is each company's share of total industry capacity for that wafer size.
Blue bars indicate the relative amount of capacity held by each company among the top 10 leaders.
Note: Includes shares of capacity from joint ventures.
Source: IC Insights

Figure 9 Installed capacity leaders in December 2020 by wafer size[25]

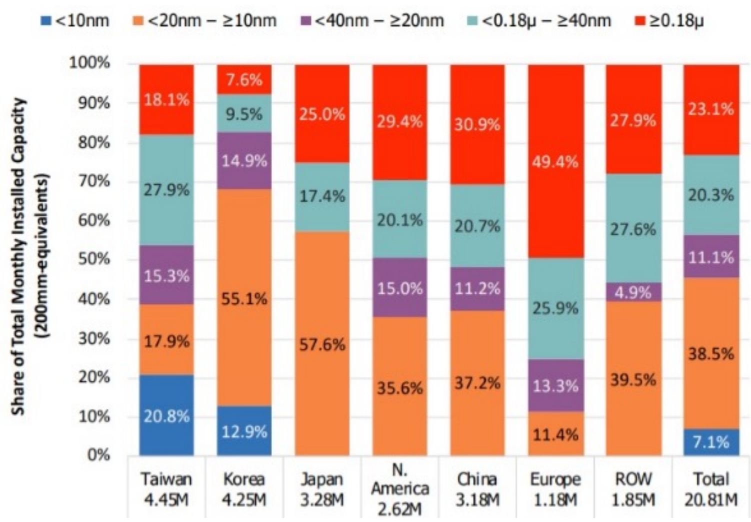


Figure 10 Monthly installed capacity for each geographic region in December 2020[26]. "ROW" means "rest of the world"

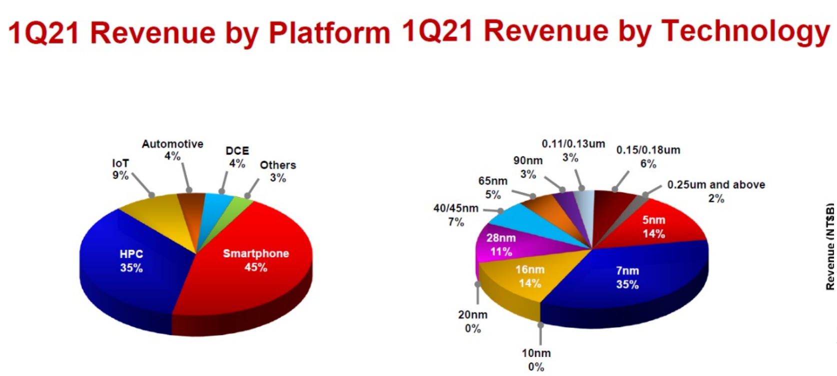


Figure 11 TSMC's 1Q21 revenue split per application and technology[27]

24 https://oecdecoscope.blog/2021/12/22/supply-side-disruptions-are-dragging-downthe-automotive-sector
25 www.icinsights.com/news/bulletins/TSMC-Ranks-In-Top10-For-Capacity-In-Three-Wafer-Size-Categories/
26 https://semiwiki.com/forum/index.php?threads/global-wafer-capacity-2021-2025.13705/
27 https://investor.tsmc.com/english/encrypt/files/encrypt_file/reports/2021-04/cf13f8bbe93d30e1c654a8711ca3aa5ebcfdcd39/1Q21Presentation%28E%29.pdf

Company	EUV shipments (unit)					
	2018	2019	2020	2021E	2022E	2023E
TSMC	**7**	**16**	**18**	**28**	**31**	**33**
Samsung	**3**	**5**	**8**	**9**	**14**	**15**
Intel	**4**	**3**	**3**	**2**	**3**	**5**
GlobalFoundries	1	0	0	0	0	0
Hynix	1	1	1	1	1	1
Micron	0	0	0	1	1	1
SMIC	0	0	0	0	0	0
Others	2	1	1	0	0	0
Total EUV shipments	**18**	**26**	**31**	**41**	**50**	**55**
EUV ASP (EUR mn)	**105**	**109**	**145**	**145**	**153**	**163**

Source: Mizuho Securities Equity Research Estimates

Figure 12 ASML EUV shipment forecast by customer[28]

While 7 nm and 5 nm represent 20% of TSMC's capacity, it is important to note that they generate ~50% of its revenue. This point is the foundation of TSMC's high-end foundry business positioning: by maintaining its leadership on advanced nodes and being the first to deliver volume manufacturing, it captures most part of the market value. This enables them to support the high CAPEX required to develop the next nodes, and install the necessary capacity (TSMC's CAPEX in 2021 is set to 30 B$). Consequently, even a company able to offer equivalent technology and spending a large CAPEX such as SAMSUNG is today having a hard time to keep up with TSMC. From a pure manufacturing standpoint, the entry barrier is high. In the short term, it may prove difficult for anyone to dispute the leadership of TSMC. Moreover, advanced manufacturing capability of 7 nm or beyond needs to come with a complex ecosystem that cannot be deployed on a very short term. Indeed, new fab players would have to build first the design enablement ecosystem (IPs, CAD flow...), and then prove to be a reliable partner, able to deliver targeted performances in large volumes and in time.

While Huawei used to be TSMC's second largest customer just after Apple, the USA export restrictions have recently reshaped the landscape. Today, most TSMC key customers for 7 nm and 5 nm technologies are USA fabless companies. The only exceptions are Samsung and MediaTek. This illustrates a key weakness of the European fabless ecosystem. Since there are currently no large European fabless or system companies requiring high volumes in extremely scaled semiconductor technologies (< 7 nm node), the current industrial drive to develop such manufacturing capabilities is rather limited. Moreover, given that China and USA are today leading in strategic topics such as AI, they are not expected to own the required manufacturing capability. As such, they are as dependent on the Taiwanese semiconductor technology.

The lack of < 20 nm node manufacturing capability in Europe does not mean that Europe is not interested in this topic. Europe's strong position on semiconductor manufacturing equipment enables Europe to play a strategic role on the value chain. ASML is a good example, since it is today the sole source of EUV lithographic scanner on the market. Figure 13 shows the EUV shipment forecast by customer and learns how leading foundries such as TSMC, Samsung and Intel are relying today on ASML (and consequently on European technology). This is a strong pledge for Europe.

The recent USA export restriction prevented Chinese companies to access to < 14 nm nodes by preventing US vendors such as Applied Material KLA and foundries to sell their US-technology based products to China. This provides perspectives concerning the position that Europe could adopt to safeguard its sovereignty, and access to key technologies related to connectivity. It is interesting to note, however, that the US has managed so far to make sure that the Netherlands prevents China from acquiring EUV equipment from ASML. The degree of sovereignty that Europe could gain from its technology leadership in selected parts of the value chain may therefore be limited.

Even if Europe does not own today the complete connectivity value chain, it has a leading position on key topics. These topics include semiconductor manufacturing equipment, manufacturing of differentiated technologies, and a leading position in the wireless infrastructure market. This enables Europe to play a leading role in future connectivity technology development, and ensures strategic manoeuvring room, by potentially strengthening its partnership with other countries.

28 https://semiwiki.com/forum/index.php?threads/will-intel-have-enough-euv-for-7nm.14191/

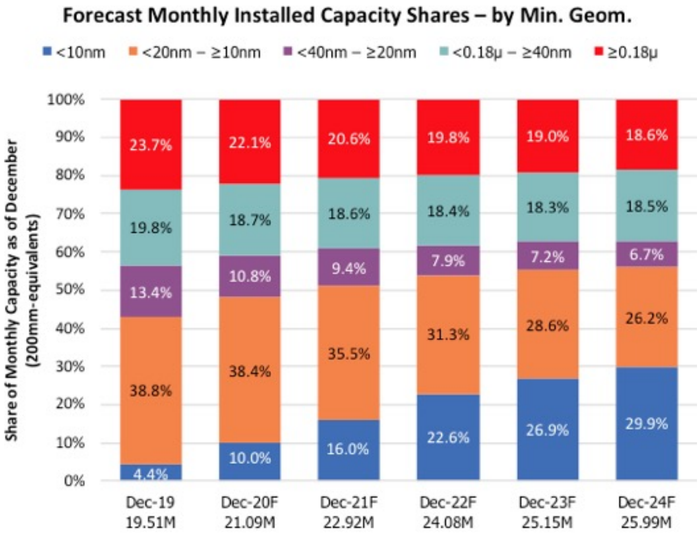


Figure 13 Wafer Capacity by Feature Size Shows[29]

Another issue is the leadership gained by the European RTOs in semiconductor science and engineering. This is critical to seed the innovations in design architectures and manufacturing technologies. With the support of European funds incentives, basic research is stimulating and attracting industry R&D, since their respective contributions are complementary to RTOs, rather than being redundant. For example, the FinFET transistor architecture, which has replaced the classical planar architecture in the recent CMOS generations, is the result of several decades of R&D collaborations. Similarly, the technology used by ASML for its flagship EUV lithography started in the 1980s, with the use of soft x-rays.

Moreover, from pure manufacturing point of view, the importance of leading-edge technology nodes versus legacy ones must be put into perspective.

Figure 13 shows that the capacity in leading-edge technology nodes will grow strongly in the coming three years while the legacy nodes will still represent a significant portion of the overall capacity (and also growing in absolute numbers).

The growing trend of leading-edge technology capacity is mainly driven by consumer products such as smartphones. As illustrated in Figure 14, leading-edge technologies are used in 89 % of the smartphone's application processor and modem, whereas only 5% of the RF and connectivity chips use such technologies. Consequently, in the smartphone market, leading-edge nodes represent 27% of the overall chip area (~7.5M 12" wafer count/year) while legacy nodes are addressing the remaining 73% (~47M 8" wafer count/year).

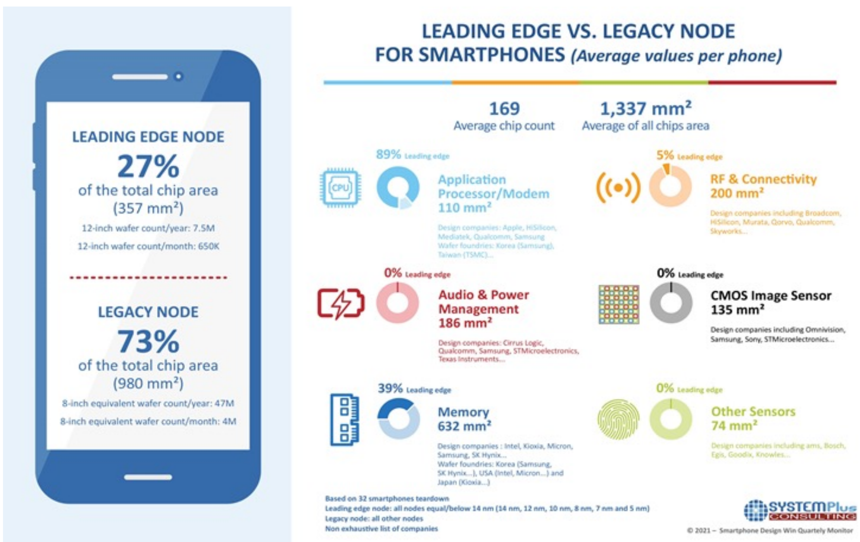


Figure 14 Leading edge versus legacy technology nodes used in smartphones[30]

29 www.icinsights.com/news/bulletins/Wafer-Capacity-By-Feature-Size-Shows-Strongest-Growth-At-10nm/
30 www.i-micronews.com/smartphone-design-win-monitor-discover-the-decisions-that-global-manufacturers-make/

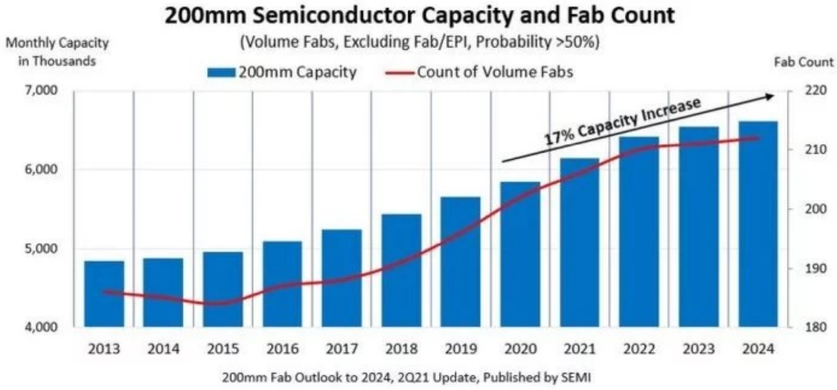


Figure 15 200 mm semiconductor capacity and count of fabs[31]

Given this persisting strong demand, the legacy technology node market will remain very active in the foreseeable future. The associated 200 mm installed capacity is expected to increase to record levels from 2020 to 2024, beating the last records seen in 2006 and 2007 (as illustrated in Figure 15). Moreover, one should also remember that European legacy technology node players are also transitioning to 300 mm fabs to increase even further installed capacity. Infineon's new 300 mm fab in Villach in Austria, STMicroelectronics' new 300 mm fabs in Agrate in Italy, Bosch's new 300 mm facility in Dresden in Germany and STMicroelectronics' 300 mm fab extension in Crolles in France are good examples of such actions.

To put it simply, there is no opposition to be made between leading-edge and legacy technology nodes. Strengthening key partnerships within Europe may secure the technology access and the European sovereignty. In the context of the Chip Act, the recent announcement of Intel's intention to build an advanced Fab in the city of Magdeburg in Germany is a good example of concrete action[32]. Not owning the complete technology portfolio does not prevent Europe to capture a significant part of the semiconductor manufacturing chain. Europe's developed technologies and associated installed might, however, remain closely linked to needs of Europe's key verticals and the European over-all position in the value chain (this comment also applies to other countries since for example TSMC is building a fab in the US targeting advanced 5 nm node to serve US fabless ecosystem while another one is being built in Japan targeting 28 nm/16 nm node to serve the Japanese image sensor and automotive ecosystems). Having such technology and processing capacity, is likely to stimulate existing and to initiate new ecosystems in Europe.

3.2 OPPORTUNITIES AND CHALLENGES

Based on the previous section, European challenges and opportunities on microelectronics and future connectivity can be summarised as follows, providing a solid foundation for the design of COREnect strategic R&I roadmap within a 10- to 15-year timeline:

Opportunities:

- Strong global position on wireless and wireline infrastructure markets and R&D.
- Strategic link between core semiconductor technology capability and key verticals (automotive, industrial, space and defence, ...).
- Combining those two assets makes Europe a strong contender to take a leading role towards 6G and beyond, while covering the entire value chain.
- Europe has strong research in heterogeneous integration for many applications (high-performance computing, photonics, RF).
- In the industrial data market, that is several orders of magnitude bigger than the personal data market, Europe should not leave the storage and handling of these data (both 'central' and 'edge') to non-European companies.

Challenges:

- Digitalisation modifies the European value chain, in which Europe risks to reduce its technological sovereignty. The rise of AI and radio access network (RAN)-virtualisation, for example, is likely to increase our dependency on USA technologies for supplying, e.g., digital logic and processors.
- Geopolitical tensions and trade restrictions impose an increased risk of disruption of the European supply chain. It is key for Europe to mitigate this risk through a more diverse and resilient supply chain.

31 www.semi.org/en/news-media-press-releases/semi-press-releases/200mm-fab-capacity-set-to-surge-21%25-to-mitigate-supply-demand-imbalance-semi-reports
32 www.intel.com/content/www/us/en/newsroom/news/eu-news-2022-release.html

3.3 STRATEGIC ACTIONS IN OTHER REGIONS

Microelectronics and connectivity are areas of strategic importance not only for Europe but for many regions of world. A brief overview of strategic actions across several major economies is presented below, in terms of legislative actions and/or investment decisions, as references for the COREnect roadmapping work.

Legislative activities in the USA

Concerned that the USA is increasingly reliant on imported microelectronics, the US Congress enacted the bipartisan Creating Helpful Incentives for Producing Semiconductors (CHIPS) for America Act[33] in December 2021 as part of the National Defence Authorisation Act, its annual defence policy update. The legislation authorises an array of R&D initiatives as well as a subsidy programme for domestic semiconductor manufacturers. However, while early versions of the CHIPS for America Act envisioned spending more than ten billion dollars over five years, the enacted version makes no specific funding recommendations for either the overall initiative or its component elements. In any case, actual funding for them will have to be provided through separate spending legislation.

On February 24, 2021, the President signed E.O. 14017, directing a whole-of-government approach to assessing vulnerabilities in critical supply chains, and to strengthen their resilience. This resulted in the release, on June 8, 2021, of findings from this comprehensive 100-day supply chain assessments for four critical products: semiconductor manufacturing and advanced packaging; large capacity batteries; critical minerals and materials; and pharmaceuticals and active pharmaceutical ingredients. For specific interest for the COREnect project are the key findings regarding semiconductor manufacturing and advanced packaging, namely:

- Promote investment, transparency, and collaboration in partnership with industry, to address the current shortage,
- ully fund the chips for America provisions to promote long-term US leadership,
- Strengthen the domestic semiconductor manufacturing ecosystem,
- Support SMEs and disadvantaged firms along the supply chain to enhance innovation,
- Build a talent pipeline,
- Work with allies and partners to build resilience,
- Protect the US technological advantage.

IIn particular, the report states that "as an initial step, Congress should fund the chips provisions with at least $50 billion in funding". Details can be found in the document entitled 100-day supply-chain review report[34].

To decrease their dependency on foreign-based semiconductor production, the USA is also making effort to attract more foreign investment. A case in point is the Taiwanese company TSMC, which broke ground in June 2021 with its $12 billion semiconductor fab in Arizona[35]. Likewise, Samsung Foundry has filed documents with authorities in Arizona, New York, and Texas seeking to build a leading-edge semiconductor manufacturing facility in the USA. The potential fab near Austin, Texas, is expected to cost over $17 billion and to create 1,800 jobs[36].

Finally, the USA is actively using export control laws to prevent mainland China from developing sub-10 nm node technology. As already mentioned, they are barring ASML from selling Extreme UV equipment to Chinese semiconductor manufacturers. They are also trying to extend that ban to older, Deep UV equipment[37].

Mainland China

In 2015, mainland China released its "Made in China 2025" initiative, which included the ambitious goal of reaching 70 per cent self-sufficiency for semiconductor production. However, they are so far falling very short of being on a trajectory meeting that target: IC production in China, including output by both foreign and domestic players, only accounted for 15.7% of its $125 billion chip market in 2019. If only companies with headquarters in China are considered, their production accounted for just 6.1% of China's total IC market that year. At its current pace China will only achieve one third of its goal.

Nevertheless, mainland China main semiconductor manufacturer, SMIC, has been increasing its R&D expenditures rather rapidly in recent years. In 2014, the company spent $189.7 million, or 9.5% of revenue, on research and development. Five years later, in 2019, the company spent $629 million, or 20.7% of revenue on R&D. In parallel, its CAPEX was expected to reach $4.3 billion in 2020[38]. On March 31st, 2021, SMIC announced 2020 sales of $3.9 billion and gross profit of $0.9 billion, while the debt-to-equity ratio "remained low"[39]. A large

33 www.aip.org/sites/default/files/aipcorp/images/fyi/pdf/chips-for-america-act-final.pdf
34 www.whitehouse.gov/wp-content/uploads/2021/06/100-day-supply-chain-review-report.pdf
35 www.datacenterdynamics.com/en/news/tsmc-starts-work-on-12bn-arizona-semiconductor-fab-gets-funding-for-japanese-chip-rd/
36 www.anandtech.com/show/16483/samsung-in-the-usa-a-17-billion-usd-fab-by-late-2023
37 www.techzine.eu/news/infrastructure/56766/usa-tries-to-prevent-all-export-of-asml-machines-to-china/
38 www.eetimes.com/smic-advanced-process-technologies-and-govt-funding-part-2
39 www.smics.com/en/site/news_read/7809

CAPEX can only be achieved via capital injection from the shareholders. Since by late 2018 the Chinese government controlled at least 46.36% of the company, this corresponds to a significant amount of public support.

Japan

Similar to the USA, Japan is also discussing with TSMC's towards the building of a chip fab in Kumamoto, which would be TSMC first Japanese semiconductor factory[40].

South Korea

The South Korean government announced on May 13th, 2021, a plan by companies to invest 510 trillion won ($451 billion) until 2030, and beefed up tax benefits, to boost chipmakers' competitiveness amid a critical global shortage of the key components. "Our government will unite with companies to form a semiconductor powerhouse. We will support companies concretely." said President Moon Jae-in[41].

As part of the effort, the Finance Ministry said it will raise the tax deduction ratio for sem-iconductor research and development investments by big companies to 40% from the current 30%, paving the way for Samsung and SK Hynix to benefit from the eased financial burden. The chipmakers also will enjoy higher deductions for investments in facilities, as the government is doubling that ratio to 6%, the ministry said.

3.4 RELATED ROADMAPPING INITIATIVES

For the preparation of microelectronics roadmap for future connectivity, the COREnect consortium and expert groups have used several roadmapping initiatives in Europe and other regions as references and baseline for its roadmapping work. A few examples were given in Table 1. Unlike these other related roadmap initiatives that have a wide scope in terms of applications, COREnect specifically focuses on developing a multi-stakeholder industry R&I microelectronics roadmap for future connectivity, using a value-chain approach and addressing digital sovereignty concern of Europe.

Table 1 Other relevant roadmapping initiatives

Document name	Related section	Date
ECS Strategic Research and Innovation Agenda[42]	Section 2.2 connectivity	01/2021
International Roadmap for Devices and Systems[43]	Focus team "Outside System Connectivity"	2020
5G ACIA white paper[44]		02/2019
Decadal Plan for Semiconductors - SRC[45]	Chapter 3: New Trajectories for Communication	01/2021
Webinar "New Apps and New Possibilities: How 5G Will Dramatically Change the Semi-conductor Industry"[46]		07/2020
"Smart networks in the context of NGI" from NetworldEurope ETP[47]		01/2021
NTT DOCOMO White Paper: "5G Evolution and 6G"[48]		02/2021

40 www.datacenterdynamics.com/en/news/tsmc-considers-chip-fab-in-kumamoto-its-first-japanese-semiconductor-factory/
41 https://asia.nikkei.com/Business/Tech/Semiconductors/South-Korea-plans-to-invest-450bn-to-become-chip-powerhouse
42 https://aeneas-office.org/pdf/sria-2021/
43 https://irds.ieee.org/editions/2020
44 https://5g-acia.org/wp-content/uploads/2021/04/WP_5G_for_Connected_Industries_and_Automation_Download_19.03.19.pdf
45 www.src.org/about/decadal-plan/
46 https://bit.ly/3iXZSyP
47 https://bscw.5g-ppp.eu/pub/bscw.cgi/d392313/Annex%20v2.3%20-%20Public.pdf
48 www.nttdocomo.co.jp/english/binary/pdf/corporate/technology/whitepaper_6g/DOCOMO_6G_White_PaperEN_v3.0.pdf

04 CORENECT STRATEGIC R&I ROADMAP

How should Europe address future connectivity technologies with a value-chain approach? COREnect proposes a multi-stakeholder strategic R&I roadmap with a 10- to 15-year timeline. This roadmap addresses different timeframes with a changing focus in terms of strategic investments, markets, and technological development in the following three strategic focus areas, in Subsection 4.1-3:

- Compute and store
- Connect and communicate
- Sense and power

To maximise the potential societal and business impact, four market segments are considered in this roadmap as detailed in Table 2. SWOT (strengths, weaknesses, opportunity, threats) analysis is carried out for those four market segments in each strategic focus area (when relevant). The key strategic actions are then identified and recommended for impacting the targeted timeline in a short-, mid- and long-term, addressing the considered four market segments, and achieving societal demands on sustainability and trustworthiness. This approach enables the consideration of the composition, strength, and resilience of entire value chains, which is essential to guarantee a sustainable technological sovereignty. In Subsection 4.4, a summary of strategic actions across the three strategic focus areas will be discussed.

Table 2 Overview of the market segments, used across the different strategic focus areas

Connectivity infrastructure	Consumer grade connectivity
Description	**Description**
Electrical and electrooptic infrastructures that enable network connectivity, communication, operations, computing capabilities and network management	Mobile devices that have sophisticated computing capability for everyday use
Scope	**Scope**
Wireless access, fronthaul and backhaul network infrastructure. Broadband base stations, radio units, access points and routers Wired (optical, electrical, ...) access, fronthaul, backhaul, metro, core and datacenter network infrastructure	Mobile phones, smart watches, and other future portable devices AR/XR devices Connected domestic robotics
Technical Requirements	**Technical Requirements**
Mild constraint on cost, size and power consumption Trustworthy: secure, safe and privacy preserving	Constraints on cost, size and power consumption Trustworthy: secure, safe and privacy preserving
Targeted customer group(s)	**Targeted customer group(s)**
Mobile, private, and virtual network operators Data center owners	Consumers, business uses, consumer healthcare
Volume	**Volume**
Tens of millions, linear growth	Thousands, millions, billions (depending on application), exponential growth

Industry grade connectivity	Automotive connectivity
Description Low-cost and low power devices for vertical applications especially in industrial environments	**Description** High-performance and low power devices for automotive applications operating in unconstrained mobility spaces and public environments
Scope IIoT, sensors, private and deterministic networks, edge computing, intelligent devices	**Scope** V2X (WLAN, cellular), sensors, mobile/multi-access edge computing, intelligent devices
Technical Requirements Extremely low power, low cost Increased security of the data	**Technical Requirements** Extremely low power, low cost High demand for security of the data and latency
Targeted customer group(s) Industry 4.0, agriculture, digital healthcare, energy	**Targeted customer group(s)** Connected and automated mobility (automotive, shipping, rail), parcel logistics and shipping
Volume Millions, exponential growth	**Volume** Millions, exponential growth

4.1 COMPUTE AND STORE

4.1.1 Introduction

For 5G, 6G and beyond, ever more performant digital computing platforms and components will be required. However, Europe is becoming increasingly dependent on non-European supply for these components and systems. This makes the European supply chain highly susceptible to disruptions such as trade wars. This chapter therefore investigates the role of computing and storage solutions for Europe's 5G and 6G sovereignty.

The architecture of programmable computing platforms, as depicted in Figure 16, is similar across the market segments identified above. It encompasses the 5G/6G system architecture, process technologies, instruction set architectures (ISAs), memory and storage, multiprocessor system on chip (MPSoC) design, and a novel operating system (OS) framework. The market segments differ in the KPIs and the operating constraints they impose on the platform and each of its components. In addition to these requirements, prospective trends and Europe's strengths, weaknesses, opportunities, and threats (SWOT) for each market segment and recommend key strategic actions for compute and storage are analysed in the following subsections.

Figure 16 Common architecture of computing systems

4.1.2 Analysis Market Segments

4.1.2.1 Connectivity Infrastructure

While the radio access network (RAN) and routing equipment, packet-core servers, and data centers are not necessarily mission critical, i.e. a failure is unlikely to have fatal consequences (at least in comparison to other applications, e.g., as autonomous driving), they still require an extraordinary level of reliability and availability and a high QoS with regards to throughput and latency. To examine this, we will have a closer look at the RAN workload.

Figure 17 shows a logical architecture of the RAN. It is a refinement of Fig. 6.1-1 of 3GPP TS 38.401. The additional interfaces (in green) are specific to the O-RAN Alliance proposal but can also be proprietary.

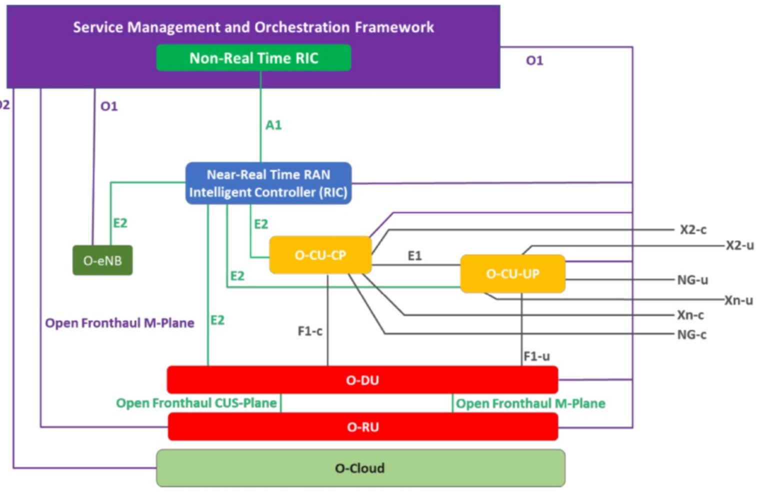


Figure 17 RAN overall logic architecture with O-RAN specific interfaces depicted in green[49]

Most of the RAN compute load is in the radio (RU), central (CU) and distributed units (DU), where (most of) the L1-L3 signal processing occurs. This workload:

- addresses multiple standards, including (3G), 4G, and 5G
- is complex, highly dynamic, and involves a large number and large variety of different tasks
- is measured in Peta-ops/sec
- has to meet extreme latency constraints, measured in micro-seconds per task
- must support so-called macro network blocks, including their activation and termination

In addition, some application functions may migrate in part to the base stations (close to the O-CU and final IoT edge AI devices).

A result of these high-performance requirements is the use of discrete components. Memories, for example, are usually stand-alone components connected via DDR interface, because the data requirements for processing and storage in this market segment cannot be met by embedded memories. The RAN compute platform will also likely be made up of multiple system-on-chips (SoCs).

A SWOT analysis of European strategic position and potential in "Connectivity infrastructure" market with respect to compute and store is summarised as follow. More details of this analysis will be found in COREnect intermediate roadmap.[50]

Strengths

- 2 out of 3 of major telecommunication infrastructure vendors
- Vertical industry ready for adoption
- Strong OS, security know-how in SMEs and academia
- Existing European virtualisation solutions, ready for adoption
- Competence in research and patent portfolio in memory and storage (TRL<=5)

Weaknesses

- Lack of strong Cloud providers in Europe
- Later deployment of newest technology compared to other regions
- Weak European industry presence and less skilled personnel in communications computing domain
- Investment in base-level software infrastructure missing
- Unaligned activities among European researchers in memory and storage
- No European products in memory and storage (no TRL>5)
- Little Influence on software landscape

Opportunities

- Digital infrastructure as foundation of society and economy
- Europe is strong in secure operating systems and hypervisors; implementations exist
- Collaboration with data centre and other infrastructure equipment companies to design own use-case optimised memory solutions

Threats

- EU unable to keep pace with US and China on AI
- EU overly dependent on supplier from other continents and vulnerable for any disruption and potential security breach
- No capability on < 7 nm manufacturing which is critical for infrastructure products
- O-RAN as an advantage for non-European silicon companies
- When we use external fabs, we give away a lot of information, e.g., about our memory designs

49 https://docs.o-ran-sc.org/en/latest/architecture/architecture.html

50 www.corenect.eu/static/5f46601a7f9764175fb38f1c/t/61e55f812036f06114037140/1642422153228/COREnect_D3.4_Intermediate_industry_roadmap.pdf

4.1.2.2 Consumer Grade Connectivity

Arguably, consumer grade connectivity is the market segment where Europe is the furthest behind in computing and storage. Consumers usually expect their devices to be of low cost, the UI (User Interface) to be familiar and software to be backwards-compatible. The factors make it hard to establish new ecosystems. For example, even a technology giant like Microsoft failed to establish a third mobile OS ecosystem besides Android and iOS. On the other hand, European customers tend to value privacy and security. This presents an opportunity for a European isolation layer that ensures security and privacy while running established eco-systems. This is definitely possible for the Android ecosystem; however, iOS devices are a closed eco-system without the option to control the hardware. A prerequisite is definitely to trust/control the hardware such that the OS/base-level software can rely on the hardware to provide isolation.

There is also the need of designing a scalable modem for UE (User Equipment). Here, the main challenge is the wide range of requirements that need to be satisfied because of many standards and use cases.

A SWOT analysis of European strategic position and potential in "Consumer grade connectivity" market with respect to compute and store is summarised as follows. More details of this analysis will be found in COREnect intermediate roadmap.

Strengths

- Strong research ecosystem in R&D centres and universities
- OS technology available for securing / virtualizing mobile devices (has been proven)
- Europe is strong in memory (storage) innovation

Weaknesses

- No strong European companies for consumer devices
- Difficult access to venture capital
- Europe is weak in selling its memory (storage) innovation
- The CMOS race is already lost for Europe
- Europe still cannot fabricate FinFET

Opportunities

- Base new systems on European values and ethical principles to improve security and user-controlled privacy, which is becoming attractive also for other regions
- Europe is strong in secure operating systems, European tech can be used to secure devices
- Master design of memory IP and MPSoCs
- Accelerate innovation in 3D integration
- Wireless storage becomes increasingly attractive
- Master fabrication of advanced FinFET
- Support Research on a new OS-based software stack with high level of abstraction

Threats

- Foreign companies (largely) controlling European data on mobile devices
- European access to memory intellectual property is diminishing
- Acquisition of innovative European SMEs by non-European technology giants
- High entry barrier for establishing new European-bred ecosystems

4.1.2.3 Industrial Grade Connectivity

Modern industrial production processes (dubbed "industry 4.0") make extensive use of connectivity for coordination and control. This involves embedded devices forming an "internet of things" (IoT) doing sensor data and communications signal processing. As failure or disruptions may lead to expensive production outages, the compute platform is mission critical. Its requirements are:

- Safety against malicious and accidental attacks
- Low latency or even real-time capability
- Scalability
- Low energy consumption.

This market segments also includes non-industrial applications that share similar requirements like home automation ("smart home") or aerospace applications (e.g., radiation-hardened processors by Cobham Gaisler).

A SWOT analysis of European strategic position and potential in "Industry grade connectivity" market with respect to compute and store is summarised as follows. More details of this analysis will be found in COREnect intermediate roadmap.

Strengths	Weaknesses
• Strong industry position on IoT, sensors and automotive electronics • Strong edge processor, OS, security know-how in SMEs and academia • Existing industrial solutions in eNVM • Stronger position in eNVM with larger IP and patent portfolio	• AI edge processing • Reliance on consumer-area products • Reliance on outside leading-edge process technologies and FPGAs • Weak links between research and industry in memory & storage
Opportunities	**Threats**
• Base new systems on European values and ethical principles to improve security and user-controlled privacy, which is becoming attractive also for other regions • Demand for low power or ultra-low power design. • European demands are or will be really high in terms of security as well as IoT, BT, industry 4.0, smart home applications. • For certain markets we clearly need to rely on European products in memory • Low-resource secure and safe OS framework	• EU unable to keep pace with US and China on AI • Big cloud providers offer integration of (their) services and IoT platforms • Reliance on outside leading-edge processes and FPGAs Security • Fleets of devices controlled by US and Asia in our premises. • eNVM technology including design and IPs are massively coming from Asia

4.1.2.4 *Automotive Connectivity*

Traditionally, automotive companies were focusing on mechanics. The mechanical units were augmented with sensors and electronic control units (ECUs) that are decoupled from each other. It is expected that these control functions will centralise transforming the car into a full-fledged compute and server platform. The introduction of autonomous driving will further increase this trend towards electronics and software. Wireless connectivity will also play an increasingly important role in new vehicles for over-the-air (OTA) software updates, vehicle-to-anything (V2X) communications, radar technologies and the combination of the latter (joint communications and sensing).[51]

Therefore, the "connected" car of tomorrow with positioning and ranging capabilities needs computation platforms that fulfil the following requirements:

- High safety
- High AI performance
- Low latency or even real-time capability.

Such computation platforms are also relevant for other mission-critical consumer devices (e.g., exoskeletons) which may be considered an extension of this market segment.

A SWOT analysis of European strategic position and potential in "Automotive connectivity" market with respect to compute and store is summarised as follows. More details of this analysis will be found in COREnect intermediate roadmap.

Strengths

- Strong automotive industry in Europe
- Strong OS position for automotive today, in-field use today
- Strong sensor and sensor processing position
- Europe is good at power electronics
- Strong research activities in the field of novel memory options in Europe

Weaknesses

- Europe's approach esp. to safety, security and regulation compared to world-wide competitors too slow
- European OEMs have additional burden of transitioning to electric drivetrains
- No design house for AI and AI engine accelerators
- No infrastructure for GDPR-compliant data set collection
- Silo research groups in the field of memory technology

Opportunities

- Europe-specific privacy regulations integrated into components and dataset collection infrastructure.
- Autonomous driving requires high security and trustworthiness
- Collect Europe-specific datasets and make them available to European AI companies
- World-wide leading platform for automotive systems.
- Unique compute unit within the car: MPSoC with cloud connectivity
- Join force with EU fabs in developing memory options

Threats

- European automotive industry moving too slow
- Softwarisation puts established processes in car companies at risk

[51] www.corenect.eu/s/COREnect-white-paper-Europes-future-role-in-microelectronics-and-connectivity.pdf

4.1.3 Identified key strategic actions

Based on previous analysis in Subsection 4.1.2, COREnect recommends the following key strategic actions in a short term, mid-term and long term, addressing strategic focus area of "Compute and Store". A summary is first provided in Table 4 and more detailed descriptions are discussed in Subsections 4.1.3.1-3.

#	Short-term (<2026)	Seg. #1	Seg. #2	Seg. #3	Seg. #4	Sus.	Tru.
Rs1.1	Build a RAN compute platform based on standard ISA for the high 5G/6G performance requirements	X				X	X
Rs1.2	Build a scalable UE modem that supports the huge diversity among 5G/6G applications		X	X	X	X	
Rs1.3	Develop RISC-V ISA extensions to enable inclusion of programmable accelerators			X		X	
Rs1.4	Support development of open modular microkernel-based OS, that can be used in safety and security contexts	X	X	X	X		X
Rs1.5	Develop an MPSoC meta-level description standard for trustworthy integration of third-party IP	X	X	X	X		X
Rs1.6	Secure access to < 7 nm CMOS technology	X	X	X	X	X	X
	Mid-term (2026- 2030)						
Rm1.1	Support research for low power eNVM for AI and confirm the industrial transfer of new memory technologies			X	X	X	
Rm1.2	Research storage-over-radio-network	X	X				
Rm1.3	Collect Europe-specific datasets for AI training with components that have privacy regulations integrated				X		X
Rm1.4	Establish <7 nm manufacturing in Europe	X	X	X	X	X	X
	Long-term (2030>)						
Rl1.1	Invest in 2.5D and 3D packaging	X		X	X	X	
Rl1.2	Design post-quantum network protocols for secure communication	X		X			X

Table 3

Summary of Identified key strategic actions where Seg. #1 corresponds to "Connectivity Infrastructure" market, Seg. #2 corresponds to "Consumer Grade Connectivity" market, Seg. #3 corresponds to "Industrial Grade Connectivity" market, Seg. #4 corresponds to "Automotive Connectivity" and Sus. and Tru. denote sustainability and trustworthiness, respectively.

SHORT-TERM STRATEGIC ACTIONS

Rs.1.1 Build a RAN compute platform based on standard ISA for the high 5G/6G performance requirements

The RAN compute platform likely is to comprise multiple System-on-Chips (SoC). These SoCs are realised in advanced CMOS, possibly including new nanoelectronics technologies such as MRAM, and are connected using novel packaging and interconnect technologies.

- Each SoC includes multiple (100s), diverse compute cores. The HW architecture is heterogeneous.
- Cost pressure and the need for software upgrades will push for programmable ISA-based cores, whereas power constraints will dictate a significant degree of specialisation, using a variety of specialised accelerators.
- These cores must be real-time capable to support their dynamic allocation on µsec-msec time scales.
- The memory organisation will be a key challenge: the need for low cost and high flexibility will push for memory unification and centralisation, whereas the need for low power will push for memory specialisation and distribution.
- The mix of cores and the memory organisation must be such that the overall multi-MPSoC RAN can be scaled over a range of workload sizes.
- Also, new system architecture design and thermal-aware and energy-aware optimisation methodologies need to be created to enable trade-offs between security, power and performance for the 5G/6G context.

Running the complex, highly dynamic petaflops workload on such a multi-SoC RAN computing platform efficiently is exceptionally challenging. It involves:

- Dynamic, real-time multi-tasking. Virtualisation is an ultimate form of this, and it is seen as the holy grail.
- Adaptive resource management, meeting power and thermal constraints during operation.

For infrastructure equipment, solutions based on application-specific adaptations of standard ISAs, such as RISC-V, which is an open-source initiative for core processor architecture design, play an important role. We identified the following open challenges and topics:

- **High Performance Chip Design:** High performance implementations in silicon are very challenging and require highly skilled CPU architects/designers (and possibly custom design at the gate level), which is currently a scarce resource in Europe.
- **Dynamic Binary Translation (DBT):** Another road to high-performance ISA implementation is using DBT to a simpler core, as done by NVIDIA with the Denver/Denver2 cores implementing ARMv8 ISA and by Apple with the Rosetta DBT. An extended RISC-V implementation could be the target of a DBT, both could possibly be in the EU skillset.
- **Adaptations of Standard ISAs (e.g., 64-bit RISC-V):** There are a few EU 64-bit RISC-V implementations: The Ariane-based from ETHZ (now on openhwgroup.org/cva6), the NOEL-V from Cobham Gaisler, the Avispado and Atrevido from SemiDynamics. It is not expected that EU-designed RISC-V processors become competitive with high-end X86 or ARMv8 implementations in USA or Asia (China, Japan, Korea) for latency-constrained applications. However, it is expected that these eventual performance limitations of EU RV64G cores will not be a major problem for accelerated computing scenarios at the edge, for 5G/6G applications. On the contrary, the ISA adaptation opportunities of the RISC-V environment will enable more tuning for these accelerated computing scenarios, in the privileged ISA (on the memory models).
- **Formal verification of ISA implementations:** Whether RISC-V related or not (OneSpin also did it on the Infineon TriCore2, on Bosch DSPs, etc.), it is of high importance to ensure trustable and reliable realisations.

Rs.1.2 Build a scalable UE modem that supports the huge diversity among 5G/6G applications

On the UE side, the main challenges arise from the huge diversity in 5G/6G modem requirements, from primitive IoT devices to high-end smartphones. This diversity is about:

- the number of standards (4G, 5G, Wi-Fi, Bluetooth, GPS, NFC, Ethernet...) to be supported,
- the ranges of required bitrates (kbps – Gbps), and latency requirements.

Accordingly, the main architectural challenge is building a scalable modem (as IP block, incl. HW/FW/SW), addressing multiple market segments.

Additional UE architecture challenges include:

- perform MIMO signal processing, support of beamforming, including distributed (coordinated) beamforming by multiple IoT devices
- additional flexibility on MPSoC to enable ISA extensions and use programmable or reconfigurable (coarse-grained or fine-grained) accelerators
- adaptive resource management approaches at system level, including power and thermal constraints at run-time during operation
- potential definition of dynamic, and real-time multi-tasking and architectural flexibility, where virtualisation can be an ultimate form of such a flexibility

Rs.1.3 Develop RISC-V ISA extensions to enable inclusion of programmable accelerators

The Instruction Set Architecture (ISA) and its realisation as a microarchitecture can be an enabling factor for innovation. In the context of 5G/6G applications, we need to consider solutions covering IoT and edge devices. For these, solutions based on application-specific adaptations of standard ISAs, such as RISC-V, which is an open-source initiative for core processor architecture design, play an important role. We identified the following open challenges and topics:

- Non-standard ISAs: Can be hidden and easily integrated into the software stack if they operate beyond a DSL; this is already the case for AI in Multi-access Edge Computing and could be the case for the L1/L2 RAN processing.
- Acceleration DSLs: May lead to specific/relaxed requirements on the accelerator memory model and the way it is seen from the GPP. Having the accelerator to operate under CAPI, CCIX or CXL may be less important than in data centres, as latency and energy-efficiency plays a crucial role in the edge.

Rs.1.4 Support development of open modular microkernel-based OS, that can be used in safety and security contexts

The Operating System Framework is the common ground for the base-level software platform that facilitates all use-cases targeted by COREnect, and beyond. All use-cases have in common that any network-connected system needs a sound base-level software platform that can fulfil indisputable requirements of security, safety, and trustworthiness, together with versatility, real-time, virtualisation and applicability to run multiple distrusting applications with diverse and potentially contradicting requirements on a single platform. The framework shall also closely follow and collaborate with hardware development for an efficient interaction between software and hardware.

Given the wide range of hardware and different applications that shall be covered, there is no "one size fits all" approach to design an operating (OS) system. The OS rather needs to be a modular system that can provide the required functionality in both features and properties such as security and safety and fully exploit the functionality of modern and future MPSoCs. Modularity enables that only functionality is included that is required, leaving out unnecessary software complexity, and allows to cluster functionality. Thereby the system can be built with multiple isolated domains. A generic OS is therefore actually a framework of building blocks, allowing to build application-specific systems and subsystems within one system such that all requirements, especially for safety and security, can be implemented. The key ability is to minimise dependencies as much as possible such that only required functionality is within the dependency of a feature. Eventually the framework allows to build, together with virtualisation technology, a hierarchy of operating systems running on the base-level OS. This hypervisor functionality is an important building block to allow for consolidation of functionality on a single platform.

Modularity is also becoming a cornerstone to the base-level software as architectures are getting more distributed by placing compute units across a platform. Distinct computing systems are not only running in the general-purpose CPUs but also in peripherals and devices, e.g., in Smart-NICs/DPUs, as well as in computing systems that are connected to the same memory or are connected via fast coherent or non-coherent connections or networks, such as CXL, CCIX, or Gen-Z.

COREnect therefore recommends that an operating system framework follows an architecture that is based on an open microkernel design, which is founded on modularity from the ground up and passes the following distinct criteria:

- A modular, microkernel-based system that focuses on security, safety, reliability, and trustworthiness: Only with small software modules it is possible to implement convincing security, safety, and real-time properties that can eventually withstand evaluation and certification as required for many important use-cases.
- Modularity also brings flexibility in system design and consequently portability and adaptability to different use-cases and upcoming hardware evolutions.
- Openness is required to establish trustworthiness of the system, allowing an independent evaluation of it. The best approach to providing the required openness is an open-source system.
- The OS software layer needs to be efficient to provide applications as much compute resources and thus minimise power consumption. Providing necessary means for controlling hardware regarding power consumption is a must.
- For a broad applicability, the OS needs a decent level of documentation and accompanying documentation such that it is generally usable.
- The system needs to provide a decent level of compatibility to be able to host existing software and applications which is typically implemented through virtualisation techniques and providing common APIs for applications.

Rs.1.5 Develop an MPSoC meta-level description standard for trustworthy integration of third-party IP

The core concept that needs to be developed at the MPSoC level is the definition of a new meta-level description standard. This new standard needs to provide common interfacing between IP blocks and units of the MPSoC to operate in real-time during run-time operation. Moreover, this standard must guarantee real-time scheduling (microsecond level) in close coordination with the OS level.

As a result, we have identified the following five core challenges and topics to cover in the design of MPSoC for the 5G/6G context to develop the aforementioned core concept:

- New MPSoC design and optimisation methodologies need to be created to enable trade-offs between security, power consumption, performance, and time-predictability in the 5G/6G context. MPSoC design is not currently real-time capable (i.e., it can fulfill hard-real time of ten μsec to few msecs latency). Therefore, to accommodate this requirement today, MPSoCs used in telecom infrastructure are massively over-provisioning the memory hierarchy (power and area wastage).
- Additional flexibility on MPSoC to enable ISA extensions and use programmable or reconfigurable (coarse-grained or fine-grained) accelerators for the compute-intensive parts of 5G/6G layers. Currently, the key elements or blocks used in this context by industrial designs are hard-coded IP hardware accelerators or FPGA devices. However, the latest communication standards need to be more flexible to enable scalable MPSoCs to increase system performance by including more specialised processors, AI chips to increase automation and heavily heterogeneous designs.
- Hardware/Software co-design of MPSoCs for the 5G/6G context requires a new higher-level software stack definition. This part must include the OS and development frameworks to exploit further application-level knowledge to understand the performance bottlenecks of different 5G/6G services and effects on the MPSoC architectural blocks. In this context, the classic use of coordination languages based on execution models, such as dataflows, is not enough. These languages are too rigid to adapt to the time-varying nature of telecommunications workloads.
- A new generation of flexible interconnects for MPSoCs needs to be added to system components and IP cores that support the real-time capabilities. These new interconnects should enable terminating and activating the macro network interfaces, such as synchronised or time-sensitive Ethernet, in the elements of the MPSoC architecture. In this context, this new generation of MPSoC interconnects has to ensure the quality of services, including guaranteed latencies and throughput.
- Definition of how to interconnect multiple MPSoCs as beamforming and other operations of 5G/6G require multiple MPSoC instances to cooperate and operate synchronously closely. Therefore, new connection standards needed for 5G/6G at the MPSoC level require to go beyond near-memory standards or classical networking interfaces to get more efficiency. In addition, at the MPSoC level, it is necessary to control functional isolation and security for the distributed infrastructure.

Rs.1.6 **Secure access to < 7 nm CMOS technology**

The future perspective of programmable computing platforms (PCP) for communications dictates the availability of semiconductor technologies with very specific characteristics. Due to, in many cases, contrary requirements of the components in such PCPs, we can already see today that those computing platforms will consist of components based on application-optimised technologies. Within the digital domain, following criteria will dominate, based on PCP requirements:

- processing speed > computational performance at low power
  - leading edge (7 nm-5 nm-3 nm)
  - thermally optimised 2.5D / 3D packaging technology
- bandwidth > RF semiconductor technologies with peak frequencies above 600 GHz
- real-time > latency > specialised hardware-based AI accelerators
  - low-power technologies for AI on value added technologies
  - low-power embedded Non-Volatile Memory (eNVM)
- cost > cost efficient and reliable 3D packaging technology for system-in-package
- trust > hardware (technology) based secure components (PUFs, secure NVM, etc.)
- sustainable > energy-efficient production and operation

Moore's Law has always been about silicon area, performance, and cost. Continuously increasing amounts of data being transferred and processed will require system components in a PCP which are built based on leading-edge digital technologies ("7 nm", "5 nm" down to "2 nm"). When neglecting the market conditions and the non-recurring costs, these technologies might be capable to resolve the trade-off between computational performance and silicon area cost. Figure 18 shows an overview of the logic/foundry process roadmaps as distributed by[52].

It should be noted that Figure 18 depicts the leading-edge offerings only. Integration of NVM, analogue, power and RF into CMOS-technologies can only be done on legacy technologies. This aspect is of high importance, as significant reductions in performance, construction size and cost can only be achieved with deeply scaled integration.

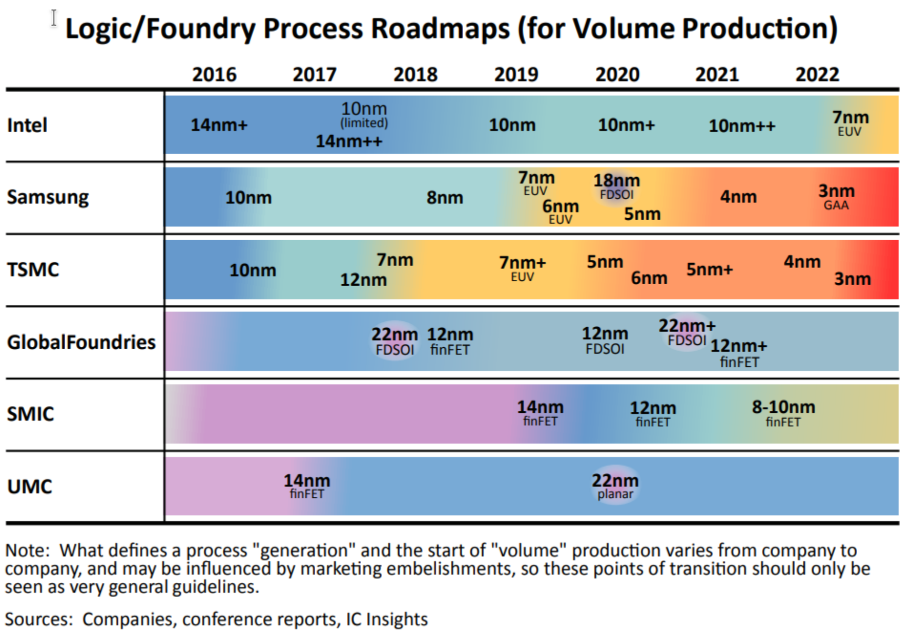


Figure 18 Leading Edge foundry process roadmap[52]

[52] www.icinsights.com/news/bulletins/Revenue-Per-Wafer-Climbs-As-Demand-Surges-For-5nm7nm-IC-Processes/

Rm.1.1 Support research for low power eNVM for AI and automotive and confirm the industrial transfer of new memory technologies

In addition to technology scaling, significant reductions in power consumption can be achieved using specialised AI components performing dedicated tasks within a PCP. These AI accelerators not only contribute to the real-time capability of the entire system. Properly designed and using AI-optimised technology components, like low-power analogue calculators and low-power embedded NVM, these AI accelerators significantly reduce system power consumption. Neither the AI functions, nor the eNVM components require deeply scaled technologies but would like to use the functional integration of moderately scaled technologies. Moreover, eNVM can only be offered in rather mature technologies, which are also available through European semiconductor manufacturers. So, the focus here must be placed more on the architecture and design of such AI components and the usage on trusted technologies from Europe in view to achieve increased sovereignty. In addition, the number of specialised AI accelerators in the PCP should be increased to a possible maximum to save as much power as possible.

On the technology level, we consider questions about eNVM improvements, e.g.,

- how to increase endurance
- how to reduce cell variance and thus enable MLC with greater numbers of logical levels
- how to reduce operational latencies
- how to reduce power
- how to reduce the process node and thus mitigate the dependency that eNVM might limit the process node for the rest of the chip

Rm.1.2 Research storage-over-radio-network

Europe has a weak industrial presence in memory and storage circuits but a strong presence in networks. Data amounts grow faster than local (on-device) storage capacity, which increases the usage of wireless storage (e.g., storage-over-radio-network, such as cloud accessed via a cellular network). Therefore, we propose as another research target the design of intellectual property (IP) for on-chip support of wireless storage (storage-over-radio-network) enabled by low-latency and high-bandwidth connectivity like 5G and 6G. For this, we need to address research questions related to the efficient integration of storage-over-radio-network into the memory hierarchy and latency / bandwidth / energy optimisations of components used in storage-over-radio-network.

Rm.1.3 Collect Europe-specific datasets for AI training with components that have privacy regulations integrated

AI continuously needs data for training. Since roads and driving styles in Europe are quite different from those outside Europe, Europe-specific datasets can be collected and made available to European AI companies to gain advantage over non-European companies and remove dependencies from them. With regulations, Europe can ensure that the dataset collection is done in a privacy-respecting manner by integrating Europe-specific privacy regulation into components. For example, the system could already blur recorded faces close to the camera sensor before the data is sent and stored.

Rm.1.4 Establish <7 nm manufacturing in Europe

Having <7 nm manufacturing in Europe will make the European supply chain more resilient. Considering the latest news that Intel is building a fab in Magdeburg, Germany, this vision is now well within reach. The fab's start of production is targeted for 2027. Intel is also investing in its fab in Ireland, with a clear target to open it for foundry services. The announced Intel 4 / Intel 3 technologies are comparable to TSMC/Samsung 5nm/4nm/3nm nodes. Other famous manufacturers may also think about building logic fabs in Europe. On the 10-year horizon we should see those fabs in Europe, if Europe really wants it. But this means building up strongly in systems business, such as telecommunications and computing. The current European strongholds of automotive and Industry will not suffice.

LONG -TERM STRATEGIC ACTIONS

RI.1.1 Invest in 2.5D and 3D packaging

Due to numerous functional components in a future PCP, special focus must be put on the system integration. 2.5D and 3D packaging technology can be used to reduce parasitic limitations (I/O loadings) and thus increase system efficiency to both power consumption and data throughput. On top, appropriate packaging technologies are capable to combine trusted components (AI, eNVM, RF) with those originating from untrusted manufacturing sources (digital "7 nm", "5 nm" down to "2 nm"). Using appropriate components providing trust, untrusted system components can be used and "upgraded" to the required trust level.

Unfortunately, standard packaging technologies are not very well represented in the European technology landscape. However, there is the opportunity to gain a lead in advanced 2.5D and 3D integration, as the technology is still relatively new, yet it has a potential of becoming a future dominator technology. Special focus will have to be placed on thermal aspects and we may have to divert some of the gains of Moore's law from "performance" to "lowering power", more than we have done in the past. Controlling 3D integration will provide us with a lead in designing security solutions and build trusted systems out of Europe independently.

RI.1.2 Design post-quantum network protocols for secure communication

Quantum computers pose a major threat to the security of today's IT systems, especially those in industry. If quantum computers with sufficient performance become available, they will suddenly endanger the current level of our information- and communication technology[53]. The great technological advances in the development of quantum computers pose new challenges for the cryptographic procedures and cryptographic methods and protocols in use today. With their increased computational capabilities, quantum computers will be able to efficiently break many established encryption methods and digital signature schemes. In particular, today's data traffic is at risk if sensitive information is tapped and stored and subsequently decrypted by a powerful quantum computer. In order to ensure data security in the future, preparations for the post-quantum computer era must begin today and new cryptographic processes must be integrated into the network's security functions.

[53] D. J. Bernstein and T. Lange, Post-quantum cryptography – dealing with the fallout of physics success, 2017

4.2 CONNECT AND COMMUNICATE

4.2.1 Introduction

Wireless communication plays an increasing large role in our lives. While today the first wave of 5G is gradually being rolled out, with the further evolution of 5G and certainly with 6G, wireless communication will become present in any aspect of human and machine interactions. While the first 5G applications operate in the frequency spectrum below 10 GHz, the so-called FR1 band (410 MHz – 7.125 GHz), the FR2 band (24.25 GHz – 52.6 GHz) will be used later for very high data rate capabilities over short ranges. The timing of the deployment can be different for each region, and it will depend on the level of saturation in the usage of lower-frequency bands. In a later phase of 5G, the FR4 band (52.6 GHz - 71 GHz) will be used. While first 5G products are becoming available, the roadmap described in this document targets the next generation 5G products and certainly 6G.

The broad deployment of wireless communication challenges the supporting connectivity infrastructure. This domain is a very important one for Europe as it has several key players in the supply chain of this infrastructure. Capacity must grow here, leading to the need of faster electronics in the transceivers.

Different domains

For the roadmap discussion in this section, we divide the field of “connect and communicate” into the following domains:

- Connectivity infrastructure:
  - Radio access networks (RAN)
  - Wired infrastructure (datacentres, optical networks)
- Consumer grade connectivity
- Industrial grade connectivity

Automotive connectivity is not treated here in a separate section, considering that from the viewpoint of wireless communication to and from a car (V2X, V2V), the car may be “seen” as a mobile terminal, as it is the case with a phone, a tablet, etc. Speed is different, latency is crucial, data rates are similar, and we can consider that connectivity to the infrastructure is similar, although with some specific properties.

Transceivers

The generic block diagram of a wireless or wireline transceiver is shown in Figure 19. In between the transmit part and a receiver (from another transceiver elsewhere), there is a medium, which can be the air, a cable, a PCB track, … The interface from the electronics to the medium is either an antenna or antenna array for wireless communication, a photodiode for optical wireline communication and a copper wire for other wireline communication. The analogue electronics make the connection between the digital part of a transceiver and the interface to the outside world. In between the analogue electronics and the digital part, analogue-to-digital converters (ADCs) and digital-to-analogue converters (DACs) perform the conversion between the analogue to the digital domain. The complexity of the analogue electronics depends on how much functionality of a classical analogue front-end is implemented in the digital domain. There is a shift towards implementing more in the digital domain. Examples are seen in digital transmitters for wireless communication and in highly digital wireline transceivers.

Figure 19 Generic block diagram of a transceiver

In this section, we refer to the microwave frequency region as the region of carrier frequencies roughly below 20 GHz, whereas we call the mm-wave region the frequency band above 20 GHz up to 100 GHz. Above 100 GHz we address the spectrum as the sub-THz band.

Microwave frequency region

A large part of this roadmap stresses mainly mm-wave opportunities and non-CMOS technologies, but the timing of adopting the mm-wave frequency spectrum on a large scale is not fixed. Indeed, if new spectrum below the mm-wave frequency is opened for cellular companies to use, it will be exploited prior to a move to the mm-wave region. This also means that innovation is still needed in the microwave frequency region. In this frequency region it is probably an illusion to let Europe take up a role in transceiver and digital baseband design for the consumer market, but there is still a role for Europe in the wireless infrastructure market and the industrial grade connectivity market. Strong investments in low-GHz CMOS mixed analogue-digital architectural innovations are key to be successful in any connectivity market. Further innovations in design reuse by focusing on flexibility are key (software defined MIMO transceivers). Moreover, combining flexibility with energy efficiency remains a key challenge and a market opportunity. Maybe O-RAN (Open RAN) developments and industrial connectivity opportunities can have interesting overlaps in mixed-signal processing and software defined transceiver hardware. Multi-market hardware may also be of interest to the European defence industry, where chip development is often not affordable given small production series.

Millimetre-wave region and the sub-THz band

The quest for more bandwidth has led to the allocation of frequency bands entering the mm-wave frequency region. With the advent of 5G, the lower part of the mm-wave spectrum is being/will be used for wireless communication. First it will be used for wireless backhaul and later for the consumer market. 5G will first use the so-called FR2 band (parts of 24.25-52.6 GHz). The spectrum around 60 GHz will be used later in 5G. While this was initially limited to the freely available spectrum between 57 GHz and 64 GHz, it is now extended to 71 GHz, and this part of the spectrum is referred to as the FR4 band.

6G wireless communication will make use of frequency bands from 5G and its predecessors but in addition use extra bands. A clear extension of the spectrum beyond 5G is the use of carrier frequencies above 100 GHz, which we address here as (sub-)THz communication. Here, the D-band will be used initially. There are two definitions of the spectrum of the D-band: the waveguide D-band is from 110 GHz to 170 GHz, while the ETSI Industry Specification Group (ISG) on mm-wave transmission (mWT) defines the D-band from 130 GHz to 174.8 GHz. In a later phase, even higher frequencies than the D-band can be addressed (e.g., the first standardisation efforts have resulted in IEEE 802.15.3d, which targets the spectrum 253–322 GHz, which is the higher part of the G-band). However, a lot of communication in 6G, if not the majority, will happen below 100 GHz, using existing frequency bands or gaps in the spectrum.

The broad deployment of wireless communication so far has only been possible thanks to the downscaling of CMOS, which came along with a speed increase of the devices. However, transistor speed, expressed in terms of the maximum frequency oscillation fMAX, at which power gain has dropped to 0 dB, is saturating to a value below 400 GHz for downscaling beyond the 28 nm generation. This means, for example, that in the D-band (roughly at one third of this 400 GHz) the maximum power gain per stage has a theoretical maximum of 3. However, in practice it is lower due to losses in passive components. Further downscaling of CMOS does not boost fMAX anymore, it only leads to a reduction of the size of digital standard cells, still giving a performance and area improvement for digital signal processing but not anymore for analogue signal processing at high frequencies.

Sustainable radio communication

The expected demand for even more wireless data communication is sustainable only if the energy consumption of this equipment is sufficiently low. This is a challenge for the digital baseband electronics: efficient algorithms, the use of machine learning and AI and the use of advanced CMOS will be required. For the analogue transceiver, the high frequency of operation is challenging when energy consumption has to be minimised, especially when the spectrum reaches out to mm-wave and sub-THz frequencies. CMOS has its limitations in speed but also in the efficient generation of transmit power generation. For power generation beyond the limitations of CMOS, a broad set of other technologies are used nowadays: LDMOS, SiGe HBT, GaN, GaAs, InP, depending on cost and form factor requirements, transmit power and frequency range. Communication systems needed to realise the scenario described in the vision, will then consist of a CMOS part for the complex operations both in the digital domain and in the analogue domain, while the parts that go beyond speed and/or power capabilities of CMOS use non-CMOS active devices. This inevitably leads to a heterogeneous system for which the integration in a 2D, 2.5D or 3D fashion is also challenged for minimal energy consumption.

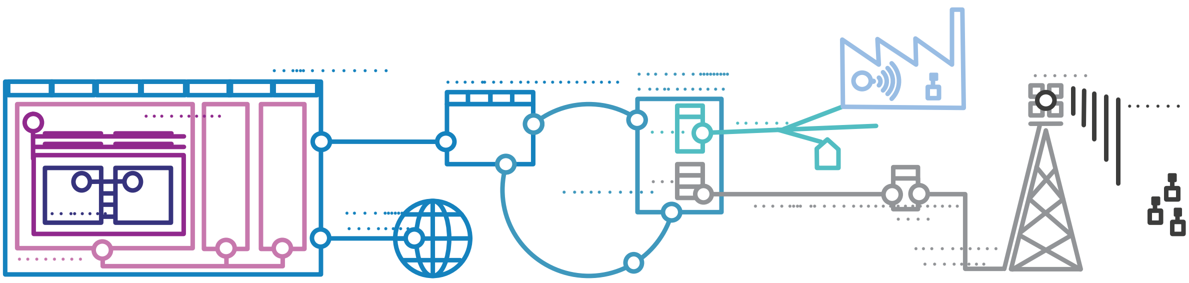
4.2.2 Analysis Market Segments

4.2.2.1 Connectivity Infrastructure

The number of Internet users - both human and machine-type users (IoT) – keeps on growing. As an illustration, IoT Analytics forecasts the IoT market size to grow at a CAGR of 22.0% to $525 billion from 2022 until 2027. This will be accompanied by a growth of the supporting infrastructure. The amount and the rate of the data exchanged with end-users will also grow. The growth of the amount of data transported inside datacentres can be expected to continue and even accelerate due to increasing reliance on novel software approaches such as AI.

An overview of the infrastructure is given in Figure 20. End-users communicate with the Radio Access Network in a wireless fashion. Inside datacentres and central offices, servers and/or racks are connected with each other. Further, there are wired inter-datacentre links and metro networks that connect datacentres and cities and long-haul networks that span continents and cross oceans. Closer to the end user, there are the optical access networks such as passive optical networks (PONs) that support fibre to the home. Finally, data generated by mobile services are carried by specialised fronthaul and backhaul links to the core of the network. In all these links the throughput will grow giving rise to higher data rates. In the wireless part the higher data rates are addressed by using more bandwidth, going to MIMO and using a higher spectral efficiency with more complex modulation schemes. In the wired communication, the higher data rates are obtained with higher spectral efficiencies, moving from NRZ to PAM-4 and even higher constellations like QAM16 in coherent transceivers.

The access points that directly interact with the end-users will cover a broad range from outdoor to indoor, from large cell to small cells or even without the usage of cells as targeted in cell-free massive MIMO. The number of wireless access points will increase significantly in the coming years due to two evolutions: first, there will be a significant increase of the number of end users both humans and machines. Secondly, when operating frequencies move up, the path loss increases, which necessitates to bring the access points closer to the end users. The consequence of having much more access points will be that the pressure on the energy consumption will be higher for sustainability reasons. As already pointed out in Section 3.2, Europe has a strong position in the wireless infrastructure market and this position should only be strengthened.



DC: Data Center
CO: Central office
DU: Distribution Unit

RAN: Radio Access Network
AAU: Active Antenna Unit
PON: Passive Optical Network

Figure 20 Simplified view of the communication infrastructure

4.2.2.1.1. Wireless infrastructure

The access points that directly interact with the end users will cover a broad range from outdoor to indoor, from large cell to small cells or even without the usage of cells as targeted in cell-free massive MIMO. The number of wireless access points will increase significantly in the coming years due to two evolutions: first, there will be a significant increase of the number of end users both humans and machines, as already mentioned above. Secondly, when operating frequencies move up, path loss increases, which necessitates to bring the access points closer to the end users. Having much more access points, the pressure on the energy consumption will be higher for sustainability reasons.

The new RAN will heavily rely on software-defined solutions, meaning that virtualisation of the RAN will be essential for 6G architectures, where the use of software-defined solutions will bring flexibility to the architecture in both terms of functionality (software) and openness (multi-vendor/hardware). Within this future scenario, Open RAN principles could be a potential approach, in particular when referring to disaggregated multi-vendor solutions.

A SWOT analysis of European strategic position and potential in "wireless infrastructure market" with respect to connect and communicate is summarised as follows.

Strengths

- Good foothold in major telecom system manufacturer market with strong system knowledge
- Strong analogue design competences.
- Presence of leading suppliers of mature and derived IC technologies
- Dynamic small and medium enterprises
- EU has much know-how - both at industrial level and in research - on packaging, 2.5D/3D integration
- EU is preparing for 6G via several initiatives (5G PPP, flagship, Horizon Europe, NetworldEurope, ...)

Weaknesses

- Few examples of technological ecosystems; Ecosystems related to microelectronics are drying up in EU
- Heavy reliance on imported semiconductors for electronics and optics. Missing main IPs (both digital and analogue)
- Few standard products to play active development role
- RF & mm-wave IC design know-how increasing, yet to be improved.
- High investment requirements to create or maintain competitive technology advantage
- EU lacks strong ecosystems in heterogeneous integration and packaging

Opportunities

- Explosive growth of wireless market expected
- Getting worldwide market leadership in 5G and beyond network wireless backhauling and the just increasing FWA market
- Increment of incentives from EU governments to establish new fabrication plants
- Foreign investments to expand the growing facilities all around Europe.
- Increasing mobile data consumption is driving new architectures of networks and transceivers (e.g. beamforming)
- Beamforming and high frequencies require advanced packaging and derived IC technologies in which EU is strong
- Innovative solutions required for lower energy consumption in combination with high performance

Threats

- Photonic and Electronic chip shortage
- Strong dependencies in supply chains
- Lack of ability to make own strategic decisions due to strong dependencies (e.g. on chips in advanced CMOS designed/fabricated outside EU)
- Market evolution uncertainty due to COVID, climate change, and geopolitical tensions
- Other regions are organizing themselves to prepare for 6G
- Non-EU competitors have very aggressive product portfolio and expertise, making high barriers to entry
- Undefined standardisation and uncertainty on future requirements for 6G networks can determine loss of R&D investment.
- Network operators may have potential cash problem to improve the network
- Rapidly growing Chinese suppliers

4.2.2.2.1. Wired infrastructure

The non-saturating quest for more data will result in a growth of the infrastructure shown in Figure 20, of the number of the datacentres and of the baud rate in wired networks. Copper cables in access networks will be gradually replaced by fibres (FTTH). Today, commercially available optical transceivers used in datacentres obtain speeds around 56-75 Gbaud per lane, but next generations will require 120...180 Gbaud and more. Roadmapping in this domain must consider that the market of datacentres and infrastructure networks is smaller than the automotive market and certainly significantly smaller compared to the handset market. The datacentre market is largely dominated by webscale companies (e.g., Facebook, Amazon, Microsoft, Google, and Apple) that even implement their own equipment. Inside datacentres, traffic is routed via a hierarchically arranged network, consisting of (top-of-rack) switches and (optical) high-speed links. The short-term challenge will be to increase data traffic handled by such switches to 51.2 Tb/s, with 100Tb/s already on some industrial roadmaps. Scaling the capacity of such switches to the 100Tb/s range will require to drastically limit power consumption, for which Co-Packaged Optics (CPO), a technology that co-integrates optics and ASICs, is a strong contender. Microsoft and Facebook have launched the CPO initiative in 2019 to enable the development of common design elements that will guide technology vendors (like Broadcom). Similarly, NVidia works on versions of its NVLink and NVSwitch relying on CPO to reduce the power consumption in the IOs of their switch and network ASICs. Electrical and photonic IC design and manufacturing activities in Europe for this market have reduced over the years, one of the reasons being the small market size. However, Europe still holds some low-volume open platforms both in industrial and research labs (imec, CEA-Leti, IHP, FhG, LIGENTEC, VTT, Smart photonics, HHI, Jeppix). Moreover, next to optical communication, photonics is present in other domains. A large growth in these domains could boost the photonics industry, from which the optical communication market could benefit. An example of such potential trigger application is the photonics-based glucose sensor in the Apple Watch or the Lidar technology for autonomous cars.

A SWOT analysis of European strategic position and potential in "Wired infrastructure market" with respect to connect and communicate is summarised as follows.

Strengths

- Strong EU research on photonics technologies & optical transceivers
- Several EU platforms for photonic ICs
- EU is strong in advanced packaging
- Strong in RF IC technologies (BiCMOS, FDSOI)
- EU dominates research on communication over plastic fibre (PMF technology)

Weaknesses

- EU does not have strong industrial players left in datacentre and optical communication ICs
- Not enough focus and involvement in silicon photonics research in Europe
- EU lags behind in design and fabrication of optical transceivers in downscaled CMOS

Opportunities

- Higher data rates and strong growth of number of end users (human + machine) requires strong growth of base stations and access points shorter to end users
- Roadmap of optical transceivers with data rates doubling every 2-4 years continues for at least another 2-3 generations
- Access via copper wires needs to be replaced by fiber access or FWA
- More digitisation in optical transceivers with increasing speed requires design of fast ADCs/DACs and complex digital ICs including DSP
- Saturating speed of CMOS gives opportunities to involve EU BiCMOS technologies in optical transceivers
- InP can cope with the increase of speed of optical transceivers beyond the capabilities of any silicon technology
- Adoption of photonics components in industries outside telecom might boost the EU ecosystem of photonics platforms
- Co-integration of optical transceivers and switch ASIC and trend to laser miniaturisation requires heterogeneous integration of chips with photonics components
- The new PAM4 interfaces (instead of LVDS) are supporting PMF (Plastic Microwave Fiber) technology

Threats

- Big players outside of EU grow fast and move on quickly to the design of ever higher-speed optical transceivers and transceiver modules
- Many EU SMEs involved in photonics integrated circuits design acquired by non-EU companies

4.2.2.2 Consumer Grade Connectivity

User equipment (UE) is by far the largest market for wireless communication. In the market today (cell phones, tablets, laptops, smart watches, ...) there is no big European player anymore. Europe has lost this market both at the level of end products and at the level of complex digital chips and transceivers. Regarding transceiver chips in the microwave region, these have almost become a commodity for sub-6 GHz 4G LTE and are designed in advanced sub-20 nm CMOS generations by Far East and USA companies. For 5G user equipment a similar scenario is about to happen – both for FR1 (410 MHz – 7.125 GHz) and FR2 (24.25 GHz – 52.6 GHz) – by lack of a big European player. Hence, intruding into the transceiver IC market for 5G and beyond looks difficult on the short term. In the communication part of UE there are only EU players left in the front-end electronics between the transceiver chips and the antennas.

UE will evolve from devices operated by humans to a mix of human-centric and machine-centric devices, giving rise to an explosion in the number of devices. For technologies such as virtual and augmented reality tremendous data rates are needed, which will necessitate the adoption of the FR4 spectrum (52.6 GHz to 71 GHz) and above, including sub-THz spectrum. UE will communicate with an access point or base station (can be an indoor one) which will have to follow the same data rate increase. An explosion of the number of end users is only sustainable if there is a strong reduction of the energy consumption per useful bit of data, even more than for infrastructure. Further, the pressure on cost and form factor is much stronger for UE. Next, the required transmit power for the uplink is much smaller than for a base station due to lower uplink data rates compared to the aggregated downlink data rate. These boundary conditions have several consequences. First, given the large market size, economics of scale will drive the big IC design players to transceiver design in recent CMOS nodes, combining analogue/RF transceiver functionality with the complex digital modem. For microwave frequencies, where beamforming is not applied, silicon-based transceivers are aided by III-V-based power amplifiers. Today, GaAs is widely used. For the lower mm-wave frequencies (28 GHz, 39 GHz) beamforming with a limited number of antennas (< 10) is used in UE. Thanks to this beamforming, the required transmit power per PA is limited and it is in reach of CMOS, although the EIRP can still be higher with III-V-based PAs. The first wave of 5G cell phones that are available today are CMOS-based, extension with non-CMOS PAs might be foreseen for next generations if price permits.

A SWOT analysis of European strategic position and potential in "consumer grade connectivity" market with respect to connect and communicate is summarised as follows.

Strengths	Weaknesses
• EU contributes to parts of front-end modules in UE • Strong research in EU on technologies for 5G/6G equipment: logic and RF technologies, packaging	• Big players in design of TRX ICs and digital modem and signal processing ICs are outside EU. No EU player left in UE end products • TRX and digital ICs use technology from outside EU • EU is losing design capabilities, both in digital with advanced technologies and in analogue/RF • Ecosystem of InP, as the device technology that is superior for operation in the D-band, is very small in EU
Opportunities	**Threats**
• Increase of carrier frequencies beyond speed or power limits of CMOS, opens the door to adopt IC technologies where EU is strong, with industrial players (e.g. BiCMOS) or R&D centers (e.g. III-V on silicon) • Adoption of phased-array technology in UE will create a large demand for complex 2.5D/3D integration	• A technology such as 6G will have a deep impact on our lives, the digital inequality will be an important point of attention • The broad deployment of 6G should remain sustainable in terms of energy consumption • Expected 6G volumes go beyond the worldwide installed capacity of non-CMOS technologies

4.2.2.3 Industrial Grade Connectivity

The focus in this section is on key connectivity technologies (Low Power Wide Area, Bluetooth, Wi-Fi, Ethernet, 5G) and microcontrollers required for industrial applications (basically industrial IoT, health and automotive). The strong European automotive ecosystem has provided a natural business opportunity for connectivity solutions developed in Europe. This comment can also be applied to other sectors, especially on the industrial market. Another explanation lies in the low cost and low power requirements of industrial applications which then call for the use of mature technologies. Most MCU solutions are manufactured today in 90 nm CMOS with a slow transition to 40 nm. Those markets are well fit for European IDM semiconductor manufacturers. This could also explain why Europe has a key role in the MCU market.

Industrial production is a major economic factor in Europe, accounting for around 25% of Europe's Gross Domestic Product. There is enormous innovation potential of IoT technologies when fully adopted not just in the production of physical goods, but in all activities performed by Manufacturing Industries, including pre-production (ideation, design, prototyping, 3D printing) and in the post-production (sales, training, maintenance, recycling) phases. Therefore, one of the major objectives of several European initiatives (e.g., Industry 4.0, Smart Factories) is to bring IoT paradigms to industry, production, and logistics demanding, amongst others, industrial grade connectivity.

From the end user perspective, i.e., production facilities taking up advanced connectivity solutions, this implies the availability of solutions that are tailored to meet demanding industrial requirements such as bounded latency and reliability, rather than more capacity. This not only implies the availability of chipsets, but the incorporation (or even customisation) of such chipsets into industrial systems and their smooth and gradual integration into existing production environments (with a plethora of other standards and protocols), step-by-step and in a modular way. From a technology perspective, this opens opportunities to innovate across the entire value chain, from the smallest components needed to enable such connectivity up to the realisation and integration of complete end-to-end solutions, possibly combining different communication systems. Further, the integration of communications and sensing may transform the way we perceive industrial grade connectivity. In this aspect, devices will sense, then locally process to some extent the sensed information and communicate.

Given the stronger starting position compared to consumer grade connectivity, industrial grade connectivity might be the best focus region for Europe to maintain and extend a position in microwave connectivity. Further innovations in design reuse by focusing on flexibility is of key importance (software defined MIMO transceivers). Moreover, combining flexibility with energy efficiency remains a key challenge and market opportunity. Maybe O-RAN developments and industrial connectivity opportunities can have interesting overlaps in mixed-signal processing and software defined transceiver hardware. Multi-market hardware may also be of interest to the European defence industry, where chip development is often not affordable given small production series.

Besides focusing on flexibility, one also needs to pay more attention to real-time operation aspects and realistic hardware/channel impairments. While much research is either focused on high-frequency (analogue) technology research and digital PHY layer research based on theoretical concepts and simulations, many end-to-end system-level aspects remain unsolved.

Dedicated chip development (in particular digital signal processing) may become affordable in specific market segments when focusing on the right features. Standardised consumer-oriented chips (like cellular/Wi-Fi) are too complex because of the requirements of backward compatibility. Such chips are closed and do not allow customisation in smaller market segments. Backward compatibility is not a main requirement in many professional new markets and deployments, where chipsets with reduced but relevant feature set can perfectly do the job. Open chip design, with open driver and firmware are key to boost end-to-end innovation (from the PHY level to the application level).

A SWOT analysis of European strategic position and potential in "Industrial grade connectivity" market with respect to connect and communicate is summarised as follows.

Strengths	Weaknesses
○ Sizeable indigenous market with strong industrial and automotive actors ○ European leaders in industry-grade solutions, from large enterprises to dynamic small enterprises ○ Proven end-to-end wired-wireless system and domain knowledge to tailor connectivity solutions to industrial requirements ○ Industry 4.0 vision originated within EU and further being developed e.g. 5G-ACIA)	○ Heavy reliance on imported general-purpose communication modules, lowering potential for low-level customisations and improvements ○ Loss of expertise on lower-level aspects (chip design, real-time operation, hardware acceleration…) due to outsourcing in the past ○ Focus of research and associated funding on higher-level software (architectures) and infrastructure, as EU depends on non-EU providers for chipsets. ○ Global spectrum licenses limiting competitiveness ○ Lack of engineers with knowledge on complete end-to-end systems (from analogue to high-level application software)
○ Emerging market with full-blown (private) 5G URLCC only to appear in coming years ○ Newly available unlicensed 6G spectrum, opening opportunities for both cellular and Wi-Fi technologies, the latter also evolving towards higher performance ○ Customisation rather than mass production, aligning with Europe's engineering and manufacturing powers ○ Increasing attention to openness (e.g. O-RAN, open chip design) to enable faster innovation ○ New radio architectures are explored for 6G	○ Dependence on non-EU providers of components and hence low-level access for customisation ○ Standardisation dominated by few big players, including non-EU competitors, introducing barriers to entry ○ Failure to attract and educate engineers within EU ○ Ignoring competing technology evolutions (e.g., Wi-Fi-6, Wi-Fi-7) and the fact that some spectrum bands are technology neutral. Less expensive and complex solutions will enter the market
Opportunities	**Threats**

4.2.3 Identified key strategic actions

Based on previous analysis in Subsection 4.2.2, COREnect recommends the following key strategic actions in a short-term, mid-term and long-term, addressing strategic focus area of “Communicate and Connect”. A summary is first provided in Table 4 and more detailed descriptions are discussed in Subsections 5.2.3.1-3.

#	Short-term (<2026)	Seg. #1	Seg. #2	Seg. #3	Seg. #4	Sus.	Tru.
Rs.2.1	Define 5G/6G system requirements for hardware components and participate in 5G/6G standardisation	X		X		X	X
Rs.2.2	Increase resources on digital IC in leading edge logic technologies	X			X		X
Rs.2.3	Build up mm-wave transceiver and front-end design capabilities and reflect on possibility to enter the market of transceivers operating above FR2 bands	X	X			X	
Rs.2.4	Evaluate the Open RAN principles	X				X	X
Rs.2.5	Research for III-V-on-Si technologies that are viable for a wide, cost-effective deployment: InP and GaN	X	X		X	X	
Rs.2.6	Invest in R&D on RF semiconductor technologies, focusing on developing <28nm FDSOI and SiGe HBT with fT, fMAX > 600GHz	X	X			X	
Rs.2.7	Join forces of research and production on 2.5D/3D heterogeneous integration	X	X	X	X	X	X
Rs.2.8	Keep up to date with and validate (private) 5G URLLC systems (trials, testbeds)			X			X
Rs.2.9	Develop optical and electronic components for optical transceivers with baud rates of 200Gbaud	X				X	
Rs.2.10	Develop co-packaged optical interfaces for new generations of switch ASICs, GPUs, CPUs	X				X	

Table 4

Summary of Identified key strategic actions where Seg. #1 corresponds to “Connectivity Infrastructure” market, Seg. #2 corresponds to “Consumer Grade Connectivity” market, Seg. #3 corresponds to “Industrial Grade Connectivity” market, Seg. #4 corresponds to “Automotive Connectivity” and Sus. and Tru. denote sustainability and trustworthiness respectively.

	Mid-term (2026- 2030)						
Rm.2.1	Attract investments to enable European manufacturing of industrial communication chips and grow ecosystem on open reference designs			X	X		X
Rm.2.2	Invest continuously in heterogeneous integration technology R&D	X	X	X	X	X	X
Rm.2.3	Develop industrial prototypes of 6G communication systems	X	X	X		X	X
Rm.2.4	Develop non-CMOS semiconductor technologies for mm-wave and sub-THz wireless	X	X			X	
Rm.2.5	Enable development of optical transceivers with baud rates above > 200 Gbaud	X				X	
Rm.2.6	Grow RF-GaN capacity	X	X	X	X	X	
	Long-term (2030>)						
Rl.2.1	Deploy modules for UE mass-market operating above FR2 band	X	X	X		X	X
Rl.2.2	Establish components (photonic and electronics) that facilitate optical transceivers with baudrates beyond 200 Gbaud	X				X	
Rl.2.3	Research on new materials for active devices	X	X			X	
Rl.2.4	Develop optoelectronics-based mm-wave and sub-THz generation and processing by heterogeneous integration with photonics technologies (silicon photonics and III-V-based)	X	X			X	

Table 4

Summary of Identified key strategic actions where Seg. #1 corresponds to “Connectivity Infrastructure” market, Seg. #2 corresponds to “Consumer Grade Connectivity” market, Seg. #3 corresponds to “Industrial Grade Connectivity” market, Seg. #4 corresponds to “Automotive Connectivity” and Sus. and Tru. denote sustainability and trustworthiness respectively.

On a short term 5G will be deployed with an initial focus on carrier frequencies below the mm-wave spectrum. In parallel with this deployment, the future of wireless communication has to be prepared for the mid- and long term where the mm-wave and sub-THz spectra will be used.

Rs.2.1 Define 5G/6G system requirements for hardware components and participate in 5G/6G standardisation

Standardisation is often dominated by large industrial players. Since EU does not have large players anymore in UE and since for wireless infrastructure the competition from non-EU players is strong, it is very important that EU players have a strong voice in standardisation that can stand the dominance of the large non-EU players.

Next to the need of advanced logic technologies for the compute functions in connectivity, the analogue, RF, mm-wave and sub-THz transceiver functionality will need semiconductor technologies different from CMOS as well as advanced packaging technologies. As technology development takes several years, it is time now to already define specifications for these technologies. Semiconductor technologies such as BiCMOS, GaN and InP will play a large role for efficient generation of wireless power. Package and antenna technologies with low losses and small parasitics such as silicon interposer and 3D integration technologies (wafer-to-wafer, die-to-wafer, die-to-die) will need to get specifications from 6G well before 6G gets deployed.

Rs.2.2 Increase resources on digital IC in leading edge logic technologies

The design of complex digital chips in EU requires that enough engineers are available for digital design in advanced CMOS technologies and that European universities and research centers provide sufficient education and training in this domain. Next to the massive digital part of ICs, the data converters (analogue-to-digital and digital-to-analogue) most often reside on the same chip as the digital part, and hence, sufficient design skills for data converters need to be present.

Rs.2.3 Build-up mm-wave transceiver and front-end design capabilities and reflect on possibility to enter the market of transceivers operating above FR2 bands

At mm-wave frequencies and above the path loss, which is the loss between the transmitter and the receiver is considerable. This can be compensated with beamforming (see Figure 21). Whereas mm-wave IC design has been mainly limited to wireless backhaul (E-band) in the era before 5G, mm-wave frequency bands will be massively deployed (on the mid- and long term), provided that the energy consumption per bit is lower compared to the narrower frequency bands used in the microwave region.

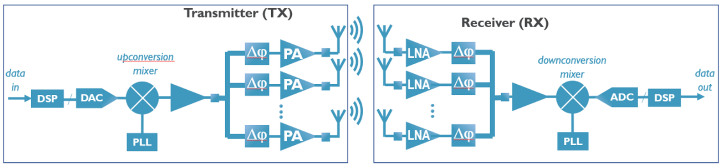


Figure 17 Beamforming in a wireless transceiver (PLL: phase-locked loop, LNA: low-noise amplifier, PA: power amplifier, ADC: analogue-to-digital converter, DAC: digital-to-analogue converter, DSP: digital signal processing, phase shifter).

Designing ICs operating at mm-wave frequencies requires extra skills compared to the low-GHz range: the transceivers, which contain the electronics to perform the frequency conversion between RF and baseband, will need new functional blocks to implement beamforming. Moreover, the design flow for mm-wave ICs is more complicated than for the microwave region. This is due to the shorter wavelength such that distributed elements like transmission lines are used next to lumped passive components. Another reason is the higher sensitivity to electrical parasitics caused by layout features and interconnects (1 fF at 30 GHz is 10x more visible than at 3 GHz). Further, mm-wave IC design requires more EM simulations.

Typically, most of the functionality of a transceiver will be based on (RF) CMOS and BiC-MOS. While at the transmit side, beamforming reduces the transmit power per PA for a required total transmit power, still the required transmit power might be too high for CMOS PAs. In that case, a trade-off can be made between the technology for the PA and CMOS for the implementation of the beamforming electronics.

While today the transceiver market is mainly dominated by US players even if the main RAN players (Huawei, Ericsson and Nokia) do develop internal ASIC solutions, the evolution to mm-wave and beamforming is an opportunity for Europe to increase its role in the market of mm-wave ICs for wireless infrastructure. This also implies that European universities and research centers should educate sufficient students and researchers for mm-wave IC design work. This should come together with a business environment favourable to startups for design houses and fabless companies.

Rs.2.4 Evaluate the Open RAN principles

Open RAN aims to create a multi-vendor RAN solution to improve network flexibility, competition, and costs. Such solution supports the functional disaggregation between hardware and software, offering open interfaces via software solutions that controls the network. The current initial deployments based on Open RAN are exploring the impact on performance KPIs (e.g., latency) due to the disaggregation, as well the impact on security. The O-RAN alliance is defining the specifications for the software-based RAN considering the specifications of 3GPP. The O-RAN alliance is an Operator oriented organisation which aims to provide the specifications and recommendations to enable interoperability among different vendors and to enable new functionality with the support of AI/ML for intelligent control and aims to provide efficient management and orchestration of the RAN.

As mentioned above, there is a strong software component in the new RAN, where hardware needs to be aligned to open RAN to be 'pluggable' in the network and easily orchestrated via the common interfaces. Therefore, it has to be evaluated how hardware could host the flexible open RAN software.

Europe needs to pay close attention in this activity. The O-RAN alliance comprises the big players (operators and vendors) from the USA, Asia, and Europe. Also, it appears that there is sufficient room for smaller players (vendors and integrators) that can innovate in the different RAN components from HW and/or SW perspective. European players need to evaluate their position in the Open RAN arena from an integrator perspective. Moreover, the emergence of the players may be associated not only to open RAN but also to companies with strong hardware (vendors) or software (vendor/integrator) expertise.

However, the Open RAN concept still lacks maturity and cybersecurity remains a significant challenge. Especially in the short term, by increasing the complexity of networks, Open RAN would exacerbate several security risks. Those risks include a larger attack surface and more entry points for malicious actors, an increased risk of misconfiguration of networks and potential impacts on other network functions due to resource sharing. The report also notes that technical specifications, such as those developed by the O-RAN Alliance, are not sufficiently mature and secure by design. Open RAN could lead to new or increased critical dependencies, for example in the area of components and cloud.

As open RAN evolves, other capabilities are expected to emerge and to further develop its capabilities related to intelligent and programmable RAN. This may pave the way for new actors like start-ups to emerge and take relevant roles. The European Commission, through the study launched on 5G supply markets and Open RAN, has certainly included Open RAN in the roadmap of the Digital Strategy for Europe, considering Open RAN as a candidate technology to be addressed by European companies (both small/medium and large companies). In the long run, operators must be able to offer connectivity based on flexible, multivendor, disaggregated architectures without compromising security, reliability, availability, QoS, and energy efficiency.

Furthermore, as cellular technologies come with their own limitations (e.g., cost, complexity, etc.), the opportunities of the newly available unlicensed 6 GHz spectrum (or others, e.g., industrial use: e.g., 3.7 – 3.8 GHz in Germany for campus networks) must not be ignored. With its large bandwidth, interesting propagation properties and anticipated Wi-Fi 6E chips, its promotion should lead to parallel high-impact innovations for industrial connectivity that stand closer to current industrial communication systems, can also serve many indoor and short-range scenarios and a lower environmental footprint. To facilitate transitions in connectivity, technology interoperability must be given attention.

Accessible testbeds and trials are needed to bring concepts to reality and verify if solutions that have been driven by standardisation in closed bodies dominated by few big stakeholders can actually live up to the requirements of players within the industrial ecosystems, including the many SMEs in EU.

Rs.2.5 Research for III-V-on-Si technologies that are viable for a wide, cost-effective deployment: InP and GaN

The generation of wireless transmit power with a high efficiency is always a challenge. Base stations operating in the low-GHz range today still use silicon-based technologies such as BiCMOS and LDMOS but RF GaN is pushing away LDMOS for better efficiency and for the higher frequencies. On the short term, the introduction of RF GaN focuses on the low-GHz range. In the medium term, the speed of GaN can be increased by scaling down the gate length. Whereas (RF) GaN on silicon carbide (SiC) is the most widely used material scheme, certainly for base stations today, GaN on silicon is a cheaper alternative. GaN-on-Si cannot handle as much power as GaN-on-SiC but it could be used for smaller-cell base stations, AAS (Active Antenna System) base stations where each single PA has quite moderate power levels or in general for applications where GaN on SiC is an overkill in terms of performance. At the foundry level, Europe has various RF GaN foundry players, both at industrial level and at research level. The European RF GaN foundry players should be able to cope with the expected growth of RF GaN and an effective spill-over from research to production is needed.

Whereas wireless applications operating above 100 GHz are not foreseen on a short term, it is time now to already invest in semiconductors for sub-THz operation. At sub-THz frequencies it is seen that Indium Phosphide (InP) devices are superior over any silicon device in terms of speed and power generation. Europe has several foundries and research centers with know-how in fabrication of high-mobility III-V devices. However, these technologies today are still niche technologies and very expensive, making use of small wafers (e.g., 100 mm). Here is a great opportunity for Europe to deploy InP to a level that can serve a mass market: elements to consider are the use of larger wafer sizes and Cu metallisation, improvement of yield, reliability, compact modelling, foundry services with available PDK, … Just as with GaN, where silicon wafers are already used as a low-cost alternative to SiC wafers, one could also consider 200 mm or 300 mm silicon wafers as a starting material and grow or reconstitute the III-V material onto silicon instead of starting from a native, smaller InP wafer.

Rs.2.6 Invest in R&D on RF semiconductor technologies, focusing on developing <28nm FDSOI and SiGe HBT with fT, fMAX > 600GHz

At microwave and mm-wave frequencies SiGe BiCMOS HBTs can generate more transmit power than CMOS and with a higher efficiency. Moreover, for the same fT and fMAX of a SiGe HBT and an nMOS device from a CMOS process, BiCMOS wafers are cheaper. SiGe BiCMOS is used today in base station chips from the low-GHz to the mm-wave frequency range. European foundries are in a strong position regarding BiCMOS SiGe, either in industrial or research organisations. Continuous improvement of the SiGe HBT fT and fMAX is fundamental for next-generation BiCMOS process platforms, to get the needed design margin for product performance robustness and to well exploit the unique feature to integrate the digital and analogue functionalities locally in each active channel of an antenna array. In contrast with a MOS transistor, the speed of a SiGe HBT transistor is not yet saturating. Predictions have indicated that fMAX can go beyond 1 THz (but at a lower breakdown voltage than an InP HBT).

Rs.2.7 Join forces of research and production on 2.5D/3D heterogeneous integration technologies

The functionality of a transceiver will be realised with digital chiplets, and analogue transceiver and front-end chips, potentially fabricated using different technologies. With beam-forming, the number of antenna paths can become so large that transceiver and front-end chips have to be duplicated. In this way, a transceiver becomes a complex compound of multiple chips augmented with an antenna array. As a result, the packaging will need advanced PCB technology or heterogeneous 2.5D / 3D integration. Interconnect pitches must be small, and losses need to be low, both in the interconnect and in the transitions to the chips (e.g., via micro bumps). Low losses are again beneficial to limit energy consumption.

As several European companies and research groups (e.g. the large RTOs imec, CEA-Leti and Fraunhofer) are strong in this domain, a transfer of their know-how to industry is an opportunity for Europe to play a stronger role at a higher level in the supply chain than solely at the level of chip design and processing.

Rs.2.8 **Keep up to date with and validate (private) 5G URLLC systems (trials, testbeds)**

Europe has a clear leadership and can take advantage of a sizeable indigenous market thanks to strong industrial and automotive actors in Europe. Integration is also happening here, the capacity to design highly integrated solutions using more advanced nodes must be secured to maintain leadership. IoT will be a key driver for this market, but without leadership on the cloud side Europe may capture a very limited part of the global value.

Compared to wireless transceivers for UE or RANs or transceivers in datacentres, transceivers operating in an industrial environment need to function in harsh environments. Key requirements for industrial communication are reliability, bounded latency and robustness rather than capacity. 5G aims to target these requirements under the umbrella of URLCC, but the entire feature set (slicing, integration with Time-Sensitive Networking, etc.) will only come with R17, targeted for standardisation in 2022 with devices 1-1.5 years later. This gives a window of opportunity of several years to focus more on design of industry-graded 5G chips and complete end-to-end systems, including 5G-enabled industrial components that differ a lot from consumer devices. The more control over the lower-level building blocks and the less outsourcing outside Europe, the more room for innovation and end-to-end solutions.

Rs.2.9 **Develop optical and electronic components for optical transceivers with baud rates of 100...130Gbaud**

To handle more data at an ever-increasing speed, optical transceivers are needed on a short term with baud rates of 130 Gbaud. Optical transceivers consist of 4 main components: the modulator and demodulator/detector optics, the analogue driver & receiver electronics (fabricated using RF CMOS or SiGe BiCMOS), the InP laser and (in many cases) a complex (DSP) SoC in advanced CMOS. Product prototypes of such SoCs using sub-10 nm CMOS have been demonstrated by several companies, many outside Europe. A few counterexamples exist such as Nokia who is designing its own 7nm DSP for 90GBaud/400G and 600G coherent systems.

There will be a need for modulators and detectors with bandwidths of at least 80GHz and front-end driver and receiver electronics with analogue bandwidths between 60GHz to 90GHz. Further, data converters will be needed in advanced CMOS with sampling rates >>100GS/s, analogue bandwidths >50GHz and a resolution of 5 to 6 effective bits.

Rs.2.10 **Develop co-packaged optical interfaces for new generations of switch ASICs, GPUs, CPUs**

To facilitate co-packaged optical interfaces for new generations of switch ASICs, GPUs, CPUs there is a need for components – both photonics and electronics – for optical communication links with ultra-high channel counts (100s of channels), a high integration density (>>100Gb/s/mm), and a high energy efficiency (< 1pJ/bit). From there we see a trend to more digitisation, requiring very high-speed data converters with a medium-high resolution (5-6 effective number of bits) and advanced packaging techniques such as MCM (Multi-chip Modules) to avoid loss at frequencies above 100GHz.

MID-TERM STRATEGIC ACTIONS

Between 2026 and 2030 the first prototypes for 6G will have to be developed by industry. 6G will first take off at frequencies below the mm-wave region. However, preparations for the 6G part that will use the mm-wave and the sub-THz frequency region need to be at speed. Meanwhile, the quest for higher baud rates in optical transceivers will continue. With these evolutions in mind, several recommendations are given below.

Rm.2.1 Attract investments to enable European manufacturing of industrial communication chips and grow ecosystem on open reference designs

EU must gain more control on industrial connectivity solutions and systems. Within the context of 5G URLCC, openness in terms of O-RAN is not sufficient. Adopters of the technology are still bound to interfaces provided by component providers, depend on the willingness of these providers to get more access or richer APIs, and are restricted with respect to end device innovations. Standardised open interfaces solutions can avoid such lock compared to proprietary solutions.

To obtain trust in components and enable customisation in a market that cannot have a one-size-fits all solution, approaches such as O-RAN must be further pushed down to the individual components, end devices and even chips. In[54], the possibility of the open-source movement entering and threatening the chip industry is discussed. For economic reasons a growth of scale is needed. This can only be achieved by standardised solutions and by ensuring interoperability between components from different vendors.

Rm.2.2 Invest continuously in heterogeneous integration technology R&D

In the field of wireless communication on the midterm, the mm-wave spectrum will be deployed and sub-THz solutions will be investigated.

The need to join forces on 2.5D/3D heterogeneous integration technologies will be even stronger then. Indeed, at those high frequencies, heterogeneous integration will be needed more due to several reasons:

- beamforming will be used, involving a duplication of the active circuitry that operates at mm-wave or sub-THz carrier frequencies;
- package parasitics have a higher impact on the electrical behaviour as frequency increases;
- due to power and speed limitations of CMOS, chips in other semiconductor technologies such as BiCMOS or III-V technologies will have to be combined with CMOS;
- efficiency of power amplifiers is lower as frequency increases, such that more heat is produced which must be evacuated via the package.

Addressing these challenges will need a continuous research effort in heterogeneous integration, which will need to ripple through to the European industry.

Rm.2.3 Develop industrial prototypes of 6G communication systems

On the mid-term, industry must be preparing prototypes for 6G communication systems to be in time for 6G deployment that is expected by 2030.

As it is expected that the first 6G deployments will be based on wireless transceivers operating below the mm-wave frequency region, these “lower-frequency” transceivers will have to be matured in this mid-term to be ready for the market by 2030. In parallel, mm-wave and D-band transceiver prototypes need to be developed. These will consist of modules combining heterogeneous integration and RF ICs some of which being developed in EU and processed with EU IC technology (Si and III-V).

54 Ian King, “Intel and Softbank Beware. Open Source Is Coming to the Chip Business”, 2020, https://www.bloomberg.com/news/articles/2020-01-22/open-source-transformed-software-the-chip-industry-is-next

Rm.2.4 Develop non-CMOS semiconductor technologies for mm-wave and sub-THz wireless applications

The speed limitation of CMOS will necessitate the use of other semiconductor technologies to cope with the need for higher carrier frequencies in wireless communication (> 100 GHz). Especially for efficient power generation at those speeds, SiGe BiCMOS and InP are superior to CMOS. The aspect of energy efficiency is very important. For example, wireless communication in the sub-THz frequency region will require much more base stations than for lower frequencies as the propagation loss between base station and end users increases with frequency.

For the implementation of the active circuits in the highest-frequency part of a transceiver, the fMAX of the device should be a factor five higher than the operating frequency. This is challenging for the SiGe-BiCMOS technologies that have been published so far. The fastest SiGe HBT published so far is from IHP and it has an fT/fMAX of 505 GHz/720 GHz. Further developments are needed to increase the speed of next-generation SiGe BiCMOS generations such that enough design margin is obtained.

Indium Phosphide (InP) devices, on the other hand, already attain speeds that provide this margin and as carrier frequencies increase to the sub-THz spectrum, InP can take over the role of BiCMOS for the highest operating frequencies. InP has already been addressed in Rm.2.4 but the effort of developing an InP technology that can be deployed at a large scale and with the inclusion of sustainability requirements during production, must be continued on the midterm.

Rm2.5 Enable development of optical transceivers with baud rates above 200 Gbaud

On the mid-term, the saturation of the speed of CMOS devices can become a showstopper to further increase of the baud rate per lane in future transceivers for applications beyond 1Tb/s (>200 Gbaud). Here is an opportunity for non-CMOS technologies that feature devices that are faster than CMOS ones, such as BiCMOS and InP.

As already mentioned above, the speed of the HBT in SiGe BiCMOS technology should be increased to leave sufficient design margin that is needed for robust design. Further, InP technology should be upscaled to a higher level of maturity (cost, throughput, yield). In this context it is also very relevant to consider efficient heterogeneous integration and chiplets. Worth mentioning is the new architecture design of very high-speed data converters (>100 GS/s) conducted by leading research teams in Europe (imec, University of Stuttgart, University of Saarland, III-V Lab, etc.) on analogue multiplexing and demultiplexing that could offer new opportunities to further extend transceiver speed.

At a higher level in the supply chain, the packaging of transceiver modules will become more complex as the increase of the data throughput not only comes from an increase of the baud rate per lane but also in an increase of the number of wavelengths, requiring more lasers. Photonics packaging is an activity already present in European research centers (Tyndall, imec, FMD, ...) and a transfer of this know-how to industry could be a means to cultivate European players in this domain. Integration approaches for photonics and electronics are needed for a dense integration of a large number of connections with bandwidths in excess of 100GHz (Multi-Chip Modules, 3D integration).

Rm.2.6 Grow RF-GaN capacity

Just as for the microwave frequency region, RF GaN is considered as a technology to generate higher transmit powers beyond the capabilities of silicon technologies. However, this requires downscaling of the channel length of GaN HEMTs to achieve the speeds required for mm-wave operation, while reliability still has to be maintained. Worth mentioning is the availability of GaN PAs for defence applications (K-band) which is a critical support for development of a new generation of GaN PAs for E- and D-bands.

LONG -TERM STRATEGIC ACTIONS

By 2030 it is expected that 6G is ready for worldwide deployment. To enable this and to make sure that by Europe has become a non-negligible player in the entire industry, we make several recommendations.

RI.2.1 Deploy modules for wireless transceivers

By 2030 the industrialisation of heterogeneous integration technology, as already addressed in Sections 4.2.3 should have taken form such that modules for 6G wireless transceivers can be produced on a large scale by European companies.

For the mm-wave and sub-THz parts of 6G, which are expected to be deployed at a large scale only after 2030, the semiconductor technologies that complement CMOS for efficient power generation (SiGe BiCMOS and InP), should be grown in capacity such that they are able to address the huge demand that is expected for 6G.

RI.2.2 Establish components (photonic and electronics) that facilitate optical transceivers with baudrates beyond 200 Gbaud

The challenge to solve for the longer term is how to achieve far beyond 100 Gbaud operation in a cost-effective, densely integrated and energy-efficient way with the constraint of speed limitations and/or high losses of current electronics and optics. What are cost-effective and industrially scalable material systems offering O/E and E/O bandwidths well above 100 GHz, while simultaneously offering monolithic integration of passive components such as wavelength MUX/DeMUX, polarisation handling, fibre coupling? What is a cost-effective and industrially scalable method to integrate the laser? InP might be a suitable material here, again implying the need for upscaling InP technology, not only for transistors, as mentioned above, but also for optical components like lasers. Further, new materials could be investigated to address these questions.

Other options for ultra-high-speed opto-electronic modulation could be the use of materials such as BTO or LiNbO3 on Silicon as a cost-effective means to realise high-speed opto-electronics or plasmonic modulators. Especially BTO is an interesting option as it allows for integration of modulators with small footprints inside a CMOS fabrication line (unlike even thin-film LiNbO3).

For backplane transceivers the transmission of radio waves over plastic fibre could be an interesting solution for the future. Initial research in this area with very strong European involvement shows very convincing results demonstrated in lab demos. With this technology data rates of up to 100 Gbps over several meters at comparably low power consumption can be achieved. Further it is evident that by increased bandwidth at higher frequencies (beyond 200 GHz) and dual polarisation, the data rate and link distance can be significantly improved.

So far, only digital optical transceivers have been addressed, in which symbols or bits are transported over fibre. With higher RF carrier frequencies being considered for wireless systems, the cell sizes in cellular networks are ever decreasing, while simultaneously the amount of traffic that needs to be transported to and from the baseband antenna masts are ever growing. This effectively implies that optical fibre is ever getting closer to the antennas themselves. Use of advanced radio techniques such as beamforming, MIMO etc. is set to further accelerate the amount of data that needs to be moved to and from the antennas and base stations. Alternative approaches to move this fronthaul data may then become increasingly important: for example, one can envision technologies such as analogue radio-over-fibre or hybrid forms being used to deliver RF signals to and from antennas. Additionally for some functionality such as beamforming optical techniques may have advantages compared to purely electronic techniques. Such microwave photonics could start to play a role at ever higher carrier frequencies, especially if integration and assembly costs of opto-electronics go down.

RI.2.3 **Research on new materials for active devices**

Instead of pushing the speed of the classical device architectures in silicon or compound semiconductors, research on the use of so-called 2D materials (graphene, hexagonal boron nitride (h-BN), transition metal dichalcogenides (TMDs), phosphorene, …) for new device types is already ongoing today. Some of these devices are promising to extend electronics to frequencies where performance of classical devices is degrading. Examples are resonant tunnelling diodes, which can find applications as oscillators operating at several hundreds of GHz, nanowires, etc.. This research requires the combination of materials research, device physics and fabrication aspects. While such know-how is present in Europe, research for new devices should be timely steered to industrially relevant applications.

RI.2.4 **Develop optoelectronics-based mm-wave and sub-THz generation and processing by heterogeneous integration with photonics technologies (silicon photonics and III-V-based)**

Advances in integrated photonics technologies (silicon photonics, III-V-based photonic ICs) need to been adopted in optical networks in telecom infrastructure and datacentres. So far, wireless transceivers consist of circuits that are purely based on electronics, not on optics. However, the unstoppable hunger for higher wireless data rates will drive the search for new spectrum to ever increasing frequencies where optical approaches might become superior for some functions that today are made with electronic circuits. With the availability of quite some photonics platforms, both silicon-based and III-V based, EU is well positioned to explore the usage of photonics for some functions in transceivers such as sub-THz frequency generation with a high spectral purity, filtering and beam steering functions.

4.3 SENSE AND POWER

4.3.1 Introduction

The key of this chapter is to identify challenges for innovations in the areas of sensing and power for future networks. The following domains will be examined:

- Connectivity Infrastructure
- Consumer Grade Connectivity
- Industrial Grade Connectivity
- Automotive Connectivity

There, it is crucial to focus on key technologies and strategic actions that enable Europe to build trustworthy and competitive solutions in all four market segments. The evolution in following areas is supported by the use of sensors and actuators enabling trustworthy and competitive solutions:

- The industrial world is moving towards smarter, more efficient and cleaner solutions with initiatives such as industry 4.0/5.0. This means moving from preventive to predictive maintenance and increasing the use of robots to improve efficiency, while preserving humans from repetitive tasks.
- Medical and healthcare is progressing to more personalised, always-on monitoring and the possibility to access medical services from the comfort of home.
- New sensor technologies will allow effortless and permanent interaction with the 5G/6G net, short-term improved voice-pickup units and midterm electronic detection and processing of signals from nerve signals.
- Transportation is evolving to higher levels of driver assistance and autonomous driving, vehicle electrification, predictive maintenance, user customisation and increased safety, alongside an evolution of smart bikes, scooters, trains, and airplanes.
- Urban management is moving towards smart cities, using networks of millions of intelligent sensors and IoT nodes to improve monitoring, manage resources, assist citizens, and improve logistics with self-driven drones and vehicles.
- Consumer and personal electronics are evolving to offer a more convenient and personalised experience. Devices such as smartphones, watches, glasses and other wearables interact seamlessly with interconnected objects in the smart home, anticipating our needs and automating routine tasks with home robots.
- Robotics, including drones, are becoming more widespread thanks to technologies developed for automatic navigation based on multiple sensors, detailed environment analysis, object recognition/detection, and tracking.[55]

However, future connectivity systems for all market segments are requiring more powerful cloud infrastructure with a consequent energy penalty and distributed sensors with increasingly complex functionality. This pushes the frontiers for edge pre-processing, energy-efficient connectivity, low latency communication, cloud computing, and AI.

Figure 23 gives a good overview on the domains and applications enabled by 6G. However, to ensure European sovereignty and leadership in the new technologies, action to favour acceptance and usage is needed.

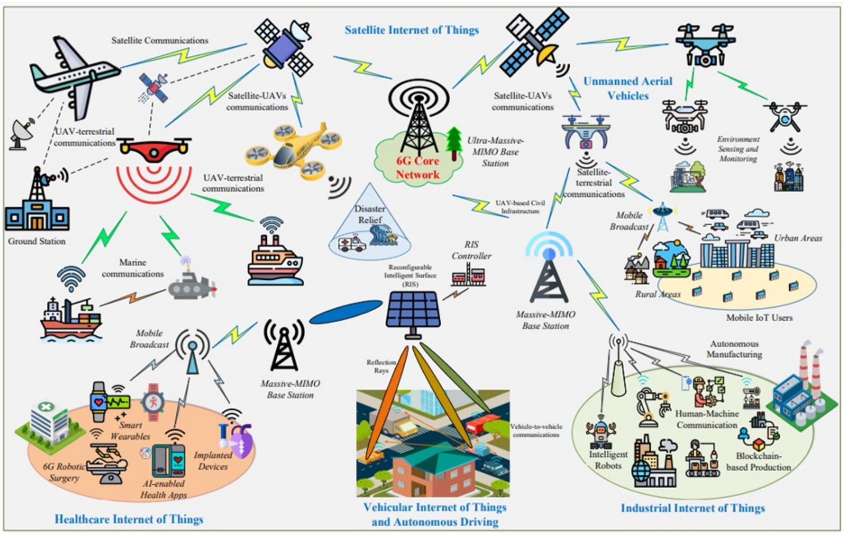


Figure 22 Vision of future 6G-based IoT applications

55 Source: Cassis, Marco (2022). Intelligent Sensing: Enabling the Next "Automation Age". ISSCC, Session 1, Plenary 1,2.

4.3.2 Analysis Market Segments

4.3.2.1 Connectivity Infrastructure

In order to enable future in-demand services at acceptable costs, future wireless access solutions must provide extreme performance in a multitude of dimensions as well as in all relevant scenarios. This includes for example extreme data rates and latency performance, when required, extreme system capacity to be able to deliver the services to a massive number of users, and truly global coverage of the wireless access. To some extent, requirements are related to the transmission of sensor data. Wireless connectivity is used for active sensing (where radio signal is transmitted solely for the purpose of sensing) and thus, allowing a base station to act as a radar system in addition to serving the communication needs of an area. This can be used to build and continuously update a map of surrounding areas to e.g., detect changes in road traffic or set off alarms if a person enters a restricted area in a factory hall. Reusing cellular systems for sensing can provide more cost-efficient sensing compared to the dedicated systems specifically deployed for sensing only.

Also, highly miniaturised devices, leveraging advances in nanoelectronics, can enable micro networks with extremely low power and range. Micro devices could be ingested or implanted to enable proactive medical care and augment human organ functionality and are expected to be built up from bio-compatible and bio-stable materials. These micro networks would consume extremely low power and could route to a full network using ultra-low-power wireless connectivity (for example, by using the 400MHz ISM band) through surface hubs that further securely communicate through an always-available link. These micro networks could be used for example to monitor drug dosages or the wear and tear of machine parts.

Table 5 describes the market sub-segment, applications, power management requirements, core process technologies, and system requirements. The focus thereby is on massive data collection and transfer, AI/ML integration and the integration of sensing and communication capabilities in future infrastructure. These refinements were addressed to define the European strategic position and the suggested key strategic actions.

Table 5 Refinement of the connectivity infrastructure market segment

Market segment	Applications	Power management	Core process technologies	System Architecture
Sub 6 GHz bands	Wireless access, sensing, IoT	Higher efficiency for lower power dissipation Formfactor Power density wireless power transfer	RF-CMOS, SoI, FD-SoI, SiGe-BiCMOS, GaN-SiC, GaN-Si, <20nm-CMOS (for complex digital) RF-MEMS RF packaging Heterogeneous integration SiP, AiP	massive-MIMO, digital beamforming, RF-FE modules, Doherty-PA, SMPA, ET, RF-DAC, DPD, digital assisted analogue/RF
mm-wave 5G				Hybrid beamforming, analogue predistortion
mm-wave 6G	wireless access, sensing, IoT			
Sub-THz 6G	RADCOM (ISAC), wireless access, cm-resolution sensing,	High efficiency for lower power dissipation Formfactor Power density	SiGe-BiCMOS, RF-CMOS, SoI, FD-SoI, <20nm-CMOS, GaAs, InP GaN-Si (for power management) RF-MEMS (micromachined Si platform) SoC, SiP and AiP integration	Digital assisted analogue/RF Massive-MIMO, distributed-MIMO, hybrid-beamforming, dual-frequency systems
Sub 15 GHz for 6G	Wireless access, sensing, IoT	Higher efficiency for lower power dissipation Formfactor Power-density	RF components & technologies, RF packaging/modules	Digital assisted analogue/RF

An overview of the technologies for RF transistors and microcontrollers can be found in Figure 23, sorted by frequency and power consumption.

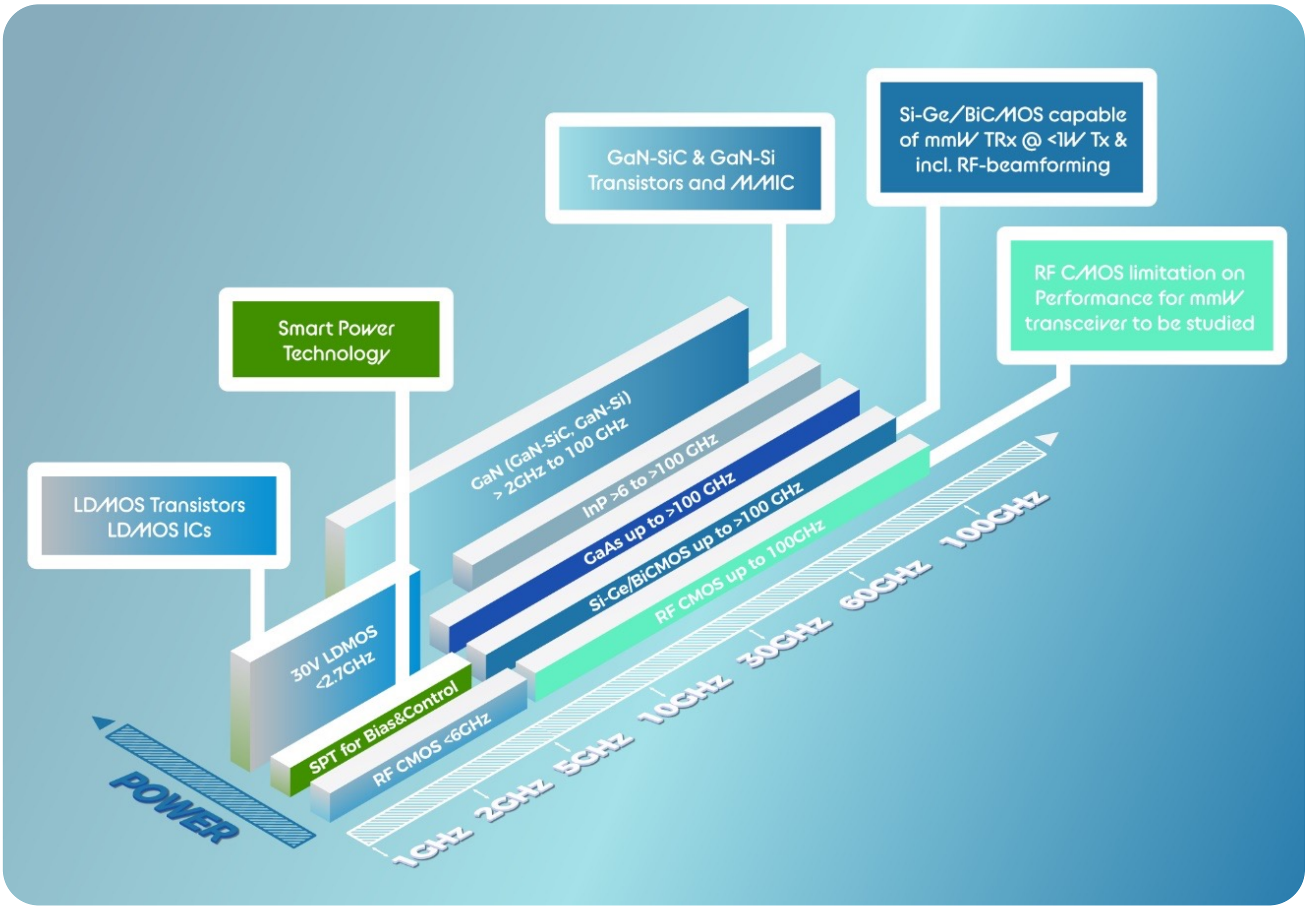


Figure 23 RF transistor and RF-IC technology overview

The SWOT analysis of the European strategic position and potential in the "connectivity infrastructure" market, considering (1) semiconductor technology and (2) RF packaging summarised as follows.

European strategic position on semiconductor technologies:

Strengths	Weaknesses
• Strong base in EU over multiple companies (ST, NXP, IFX, UMS, OMMIC,) and ODM (Ericsson, Nokia); Bosch • Key equipment supplier from EU (ASM, ASML, Besi, SPTS, EVG, Boschman, etc.) • Research base in EU (Fraunhofer, IMEC, CEA-Leti, TNO, Tindall, IHP, FBH, ... • Semiconductors and materials education in universities • Extensive IP (patent) portfolio • "More than Moore" semiconductors R&D and production in Europe (power, RF, MEMS, ...)	• Industrial base for expansion in Taiwan and China • RF ICs design process is low automated (analogue vs. digital design tools) • User equipment company missing in EU • Consumer electronic reference design makers (Qualcomm, Broadcomm, Intel) US based
Opportunities	**Threats**
• EU based manufacturing focused on strategic vertical domains to reduce dependencies (e.g. automotive, communication & industry) • AI algorithms to improve chip design and manufacturing as well as system design • Governmental support on speed up of frequency allocation for communication (Wi-Fi and 6G) • Big public support for "green transition" • Enable green transition	• Slow decision and scattered interests of member states • Fragmented specialised RF field makes investment risky • International companies impacted by US bans • Tough competition due to large size of subsidies in China and USA (Darpa) on manufacturing process • Slow move from R&D to production • Missing pilot lines

European strategic position on RF packaging:

Strengths	Weaknesses
• Strong patent position • Strong institutes (FHG, Imec, TNO, CEA Leti) • Industrial base with several packaging companies (e.g. PINS, AMKOR Portugal, Sencio, etc.) • IC companies (users) with package research and knowledge	• Industrial base of OSATs (and ecosystem) dominated by Far East • ODMs industrial base is limited in EU • Industry has volume and price focus over innovation and location of production • Lacking specialisations on packaging within universities
Opportunities	**Threats**
• Increasing complexity requiring high end packaging (and the evolution towards high volume at consumer prices) • Use regulations to shape this industry to be compliant with long term green & human goals of EU • EU subsidy program to focus on EU strategic development	• Tough competition due to large size of subsidies in China and USA (Darpa) on manufacturing process • Slow decision and scattered interests of member states • Big Tech companies (Apple, Alphabet, Meta, Microsoft, Amazon) are US/Pacific oriented

4.3.2.2 Consumer Grade Connectivity

Consumer grade connectivity and sensors are a very important part of the microelectronics value chain. Almost all consumer electronics and home appliance manufacturers are figuring out ways to get an edge by offering smarter gadgets. These products address today's lifestyle, which is all about convenience. Internet-connected devices and smart homes provide a way of enabling that living. We are rapidly becoming accustomed to connected devices like home assistants, video doorbells, smart locks, smart televisions, alarms, and many other appliances. In the health and wellness environment, connected devices are used for example as wearable health trackers and are even managing your medication. As for health and medical applications, all the requirements like security, reliability, low-power and small form-factor are most relevant, this area will be the main focus in this section.

Improvements in acoustic sensing principles and other Human-6G-interface technologies will open the door for a permanent and effortless interaction with the internet. This will enable health, voice, and gesture monitoring equipment to be compact and portable, which opens opportunities for consumer healthcare and human-computer interfaces. There, the consumer devices are used for communication, fitness, and wellbeing applications. They do not require a medical approval and can be purchased in any retail store.

On the other hand, the medical/healthcare devices that depend on approval from healthcare organisations require prescription. Regarding the fusion of both, those functions and requirements are combined in the consumer healthcare sector (see Figure 25). In the transformation of healthcare organisations, the COVID pandemic has accelerated technology requirements toward a patient centric approach: more telehealth, more wearable, hearable and connected medical devices & more prevention through continuous monitoring. Thereby, the rising prevalence of chronic conditions (diabetes, obesity, etc.) and the outbreak of COVID are key drivers of the market.

The integration of 6G will revolutionise the way health monitoring and healthcare will be solved, moving towards a holistic healthcare system equipped with data from prevention to diagnosis and treatment up to homecare. The effortless monitoring of body parameters and the permanent accessibility of medical support will allow an efficient and huge improvement in public health and wellbeing. An important example is the potential use of 6G technologies for supporting extremely low-latency healthcare data transmission and accelerating medical network connections between wearables and remote doctors.[56] An overview on the performance improvement from 5G to 6G is shown in Table 6.

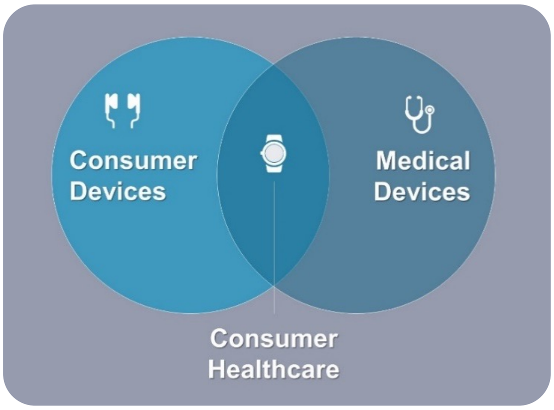


Figure 24 Consumer healthcare is a new application domain, emerging from fusing consumer electronics with medical devices

Table 6 Expected performance improvement from 5G to 6G

	5G-IoT	6G-IoT
Data Rate	20 Gb/s	1 Tb/s
Mobile Traffic Capability	100 Mb/s/m²	1 Gb/s/m²
Connectivity Density	10E6 devices/km²	10E7 devices/km²
Network Latency	1 ms	10-100 µs
Coverage	70%	>99%
Energy Efficiency	1000 x 4G	10 x 5G
Spectrum Efficiency	3-5 x 4G	>3 x 5G

[56] D.C. Nguyen, P.N. Pathirana, M. Ding, A. Seneviratne, "Blockchain for 5G and Beyond Networks: A State of the Art Survey", Dec 2019.

As shown in Figure 25, many remote systems in the healthcare domain, e.g. remote health monitoring, remote surgery, and haptic application require low latency communications with the reliability requirements of above 99,999%. 6G robotics can be applied to implement remote surgery in a fashion that remote doctors can manage the surgery via the robotic systems in the context of 6G at a latency of milliseconds and high reliability. The ultra-low network latencies (10-100 µs) fulfils the requirement of haptic applications such as e-health and autonomous driving. A telesurgery system in the context of 6G, UAVs, and blockchain is exemplary studied in[57]. Due to the use of blockchain technology, each robot acts as a data node so that surgical information is stored securely in the database ledger without the need of centralised authority. Accordingly, wearables, on-body sensors, implants, body area networks, and nano-sensor-devices can communicate and transmit data in real-time with extremely high reliability and availability to edge devices or cloud centres for preventive-, short-, and long-term medical analysis. 6G-based Ultra Reliable and Low Latency Communication has been exploited to facilitate connected ambulance in future healthcare, by allowing real-time video streaming with high colour resolution for reliable diagnosis to clinicians and paramedical staff from the hospital at moderately high speeds.

New business models will appear with medical equipment manufacturers growing into data service providers (Medical Edge). Thus, the data storage will require a high security level. The integration of blockchain and Mobile Edge Computing with its decentralisation, immutability, and traceability features potentially offers high degree of security and privacy to healthcare operations, e.g. secure Electronic Medical Records. In the digital healthcare era, it is of utmost importance to share Electronic Medical Records across healthcare institutions to support collaborative health services and achieve universal healthcare[58].

Another opportunity is to adopt edge cloud computing to provide low-latency health data analytics for healthcare services such as diagnosis, disease prediction, and intelligent decision-making tasks for physical medicine and rehabilitation. In this context, ML is also useful to optimise mobility management processes by taking data rates, traffic flows, data processing delays, and bandwidth resource allocation into account. Implementation results show a good trade-off between time and energy efficiency by using ML techniques while effectively managing and monitoring the mobility of the IoT driven devices in 6G-empowered industrial applications (including healthcare services). Wireless and wireline communication technologies such as Ultra Reliable and Low Latency Communication, edge intelligence, and cloud computing have been applied to combat the COVID pandemic in different ways. In future, a regular and online monitoring with Intelligent Wearable Devices will increase the efficiency and quality of the public health system dramatically.

Figure 25 New application areas and an interconnected medical IoT arise with 5G/6G

57 R. Gupta, A. Nair, S. Tanwar, N. Kumar, "Blockchain-assisted secure UAV communication in 6G environment: Architecture, opportunities, and challenges", February 2021, https://doi.org/10.1049/cmu2.12113.

58 J. Indumathi, S. Achyut, G. Muhammad, J. Gitanjali, H. Qiaozhi, W. Zheng, Qi. Xin, "Block Chain Based Internet of Medical Things", IEEE Access, Special edition on now advances in blockchain wireless networks, October 2020.

Intelligent wearable devices will be connected via 6G to the Internet and transmit physiological and physical data to test-and monitoring-centres. These devices will monitor heartbeat, blood pressure, blood tests, health conditions, body weight, and nutrition, deliver quick results, and will save and store the personal history of health, nutrition and habits. Also, the system will learn from the personal body history and advise the person for the next physical activity or nutrition to prevent and cure diseases. The detection of minor body issues such as deficiency will reduce the frequency of hospital visit[59].

A SWOT analysis of the European strategic position and potential in the "Consumer grade connectivity" market with respect to sense and power is summarised as follows. More details of this analysis will be found in COREnect intermediate roadmap.

Strengths	Weaknesses
• COVID breath analysers from EU Companies (Imspex diagnostics, Wales; Breathomix, Netherlands; RAM Group, Germany) • Big medical players in EU (Siemens AG, Philips, …) • Trustworthiness as high priority in Europe • Advanced electronic sensors and photonics, MEMS • European strength in robotics	• Market is fragmented, many small players with distributors (non-European) • Distributors might not be trustworthy (in case of chip shortage low priority on security) • Slow innovation; point solutions and low volume; strict regulation • Discrepancies between Pharma, MedTech & ECS (Electronic Components and Systems industry) • Quite a distance to competitors in advanced CMOS nodes • AI chips for healthcare wearables • Chip production is still done mainly outside EU.
Opportunities	**Threats**
• Strong market growth due to nanotechnology based biosensors, molecular biology • Open technology platforms, shared standards in medical technology promoted by the European alliance MedTech Europe. • Consumer healthcare to penetrate medical market • Remote surgery with high end robotics will gain importance	• Distributors in Hongkong, China, US might dominate the market • Apple/fitbit etc. advantage in big data collection & handling

59 S. Nayak, R. Patgiri, "6G communication technology: A vision on intelligent healthcare", Studies in computational intellegence, Springer, 2021.

4.3.2.3 Industrial Grade Connectivity

In the vision of ambient intelligence, the ability to gather detailed and accurate information is key and relies mainly on smart intelligent sensors able to measure and communicate. Numerous studies envisioned several billions of sensors, tags and small IoT devices in the next few years. However, it appears that the need to power those devices through batteries or main AC power is a key limitation for their deployment, mainly for cost, operational, and environmental constraints. Therefore, the ability to produce battery-less devices, able to extract the power they need from their environment, is crucial to enable the wide deployment required by a highly efficient environment. This will have implication on the industrial applications (logistics, building automation, smart cities, ...) and on the consumer market.

The evolution of the traditional industrial systems towards Industry 4.0 and Smart Manufacturing creates a highly dependable Industrial IoT (IIoT) ecosystem of connected, heterogeneous, and complex production systems characterised by increased dynamicity in configuration, system context, system environments, and tasks. IoT-enabled industrial infrastructure differs from traditional communication networks in terms of security, safety, resilience to failures, and reliability requirements, which now become increasingly important and pervasive, while digitalisation and connectivity are gradually manifesting themselves as the new business reality and a game-changer in many industrial sectors.

Lower cost of energy-harvesting function and more efficient ultra-low-power components open the gate to widely disseminated battery-less communicating devices, even for "almost disposable" usage (e.g. parcel tag European companies to take advantage of much more efficient supply and shipping capacity using smart tags). In the long term, universal energy harvesting devices are able to use jointly different energy sources to cope with every situation and support critical services (roadside infrastructure). Not only does the devices' power consumption require to develop energy harvesting capabilities (solar, electromagnetic field, heat, vibration...), but it also implies to both develop extremely power-efficient electronics (MCU, sensing, analogue, RF, power management) on one side, and an expertise on energy-efficient software coding on the other side as shown in Figure 26.

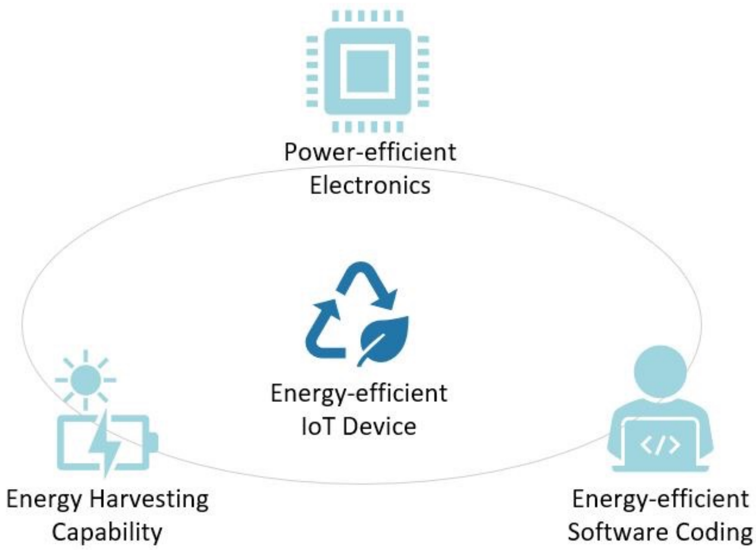


Figure 26 The key areas contributing to energy efficiency in battery-less IoT devices

We focus here on key technologies required to support new generation connectivity in industrial markets. When looking at industrial sites, the main applications in focus are industrial grade wearables, IoT for remote machine control smart metering, ultra-wide bandwidth sensors and gesture recognition. However, the same technologies find broader usage in modern agricultural sites, smart cities, smart homes and smart buildings with very similar and sometimes more demanding performance constraints. The diversity and complexity of new connectivity requirements are driving businesses to review their strategy and seek new solutions. Public cellular networks do not give the local control and flexibility required in private networks (networks installed by enterprises) in the way that Wi-Fi does. On the other hand, Wi-Fi is not designed to cover large areas, connect large number of devices or to be used for critical communications. 5G networks are a new standard capable of responding to new needs and offering unimaginable opportunities for industry and society.

One of the main fields with large innovation potential is IoT technologies employed throughout all industrial activities from production to transportation, logistics, and retail. Wide adoption of IoT technologies is possible only with industrial-grade connectivity as depicted in Figure 27. To control and monitor production, smart sensors can be used on the factory's floor. For low latency human-to-machine and machine-to-machine communication, smart wearable devices represent the next step to improving productivity. AR Glasses, VR Headsets, Smartwatches, Smart Bands are some examples of smart wearable electronics, used not only in tasks like package handling, truck loadings, tasks in warehouses and production lines, retail and transportation operations, but also to ensure employee's health by monitoring posture, movements and for remote assistance and training.

Smart farming and digitalisation of the agriculture are already a strong focus of the European community. IoT sensors collect environmental and machine data, which farmers can exploit to make better decisions as well as to improve every aspect of their work, such as crop farming and livestock monitoring. Indoor farming and aquaculture among other aspects greatly benefit for deployment of smart sensors and improved connectivity. A combination of IoT real-time data with accurate geospatial data is the key enabler of truly precision farming.

Figure 27 6G and the industrial IoT will enable new capabilities within the existing infrastructure

The COVID pandemic, mounting decarbonisation commitments, resource constraints and continuous urban growth are reinforcing the need for making the cities smarter, more efficient, and sustainable for their residents. The reduction of carbon footprint requires adoption of key technologies like smart grids, micro-grids to use and share local energy sources, next-generation energy transmission, distribution networks with automatic monitoring of energy flows and adjustment to changes in supply and demand. It is clear that these innovations require changes to urban infrastructure and accelerated deployment of new technologies including 5G, AI, cloud, and edge computing, which is helping to drive the evolution of Smart Cities with IoT sensors distributed all over the city's territory. The extended connectivity drives the need for high reliability and security of the network. This makes it necessary for telecom and technology companies to collaborate among themselves and with the government and invest in reliable networks, cybersecurity, and backup systems.

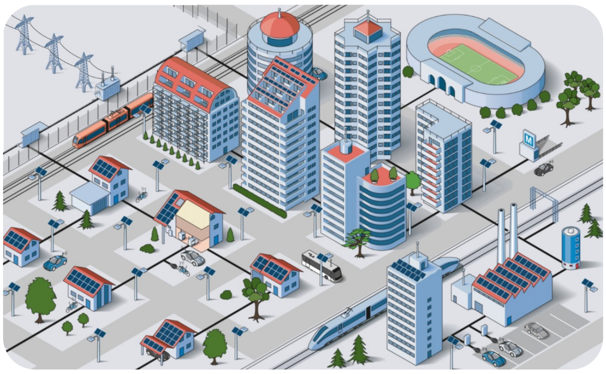


Figure 28 Smart, energy-efficient buildings are interconnected in the Smart City

Decarbonisation can be addressed not only at city level, but also down to buildings and house levels. Commercial buildings account for 20% of energy use in the US, of which 30% is wasted. Smart solutions pave the way to make them energy-efficient and sustainable, whilst automated management allows expansion of the building's nervous system into a network of smart buildings. Key elements of this transition are smart sensors, which generate detailed, real-time data about the building, from occupancy to ventilation, lighting, and power demand. Smart buildings should be capable of adjusting their power consumption in real-time communication with the city's grid and using local storage elements. For example, excess heat produced by office buildings can be transformed into locally stored energy, which can be used in case the grid requires temporary reduction of the energy consumption.

One of the fundamental topics to be addressed is how to manage power of all these sensors and how to handle the huge amount of data generated by them. A SWOT analysis of the European strategic position and potential in the "Consumer grade connectivity" market with respect to sense and power is summarised as follows. More details of this analysis will be found in COREnect intermediate roadmap.

Strengths

- Big player in ultra-low power component (STM, CSR, Nordic) and in RFID (which is the precursor).
- Big player in wide bandgap (SiC, GaN) devices that allow for greater power efficiency, smaller size, lighter weight, lower cost.
- A lot of European research efforts in IoT technologies.

Weaknesses

- Chip production is still done mainly outside EU.
- Material availability for the main components (batteries and semiconductors).
- Many materials need to be imported for power generation in the EU (e.g. oil, fossil fuels, gas).
- Lack of collaboration between universities and industry in the high efficiency power field.

Opportunities

- Transaction for autonomous devices will increase in the future for many reasons, including environmental constraint and maybe regulation
- European commitment towards climate neutrality increases demand for solutions reducing energy demand in the industrial sector.
- Renewable sources as a good opportunity for alternative power generation in the EU. This is accompanied by connectivity and smart orchestration based on sensors.
- Leveraging the know-how in communication for increasing international business and/or collaboration on an exchange base.

Threats

- US and Chinese actors are also very active on RF Energy harvesting and China is sensitive to supply chain optimisation.
- Supply chain disruptions of critical materials needed for semiconductors, solar panels, batteries, rare earths.
- Political strategy changes on zero-emission targets and technical developments affecting research efforts in sensing and power areas.

4.3.2.4 Automotive Connectivity

Automotive connectivity is evolving very rapidly. Whereas in the past a vehicle consisted of "connectivity islands", which connected the car to the outside with a single link to the internet. Now, the vehicle is more and more evolving towards highly networked device with direct links between vehicles, other road users and road infrastructure components as traffic lights as well as with links to the cloud and edge clouds. In addition, the connectivity within the vehicle to connect control units to each other and connect the passengers to the vehicle and the outside world is increasing.

The need for connectivity arises mainly from the evolution from ADAS (Automated Driving Assistance Systems) to fully autonomous vehicles as well as transferring and processing all the data gathered from traffic monitoring and management. High level of vehicle automation demands full awareness of vehicle external environment, with 360-degree vision and peerless driving skills. The potential of connected and autonomous vehicles will be fully unleashed through vehicle-to-everything wireless communications, providing connectivity to and from cellular base stations among vehicles. Sensing thereby will have to become a feature offered by the network including all kinds of spatial monitoring. Thereby different types of radar and other sensing elements will have to be integrated with communication and connectivity networks and devices. From the semiconductor perspective, research and development of core process technologies (e.g. as defined in Table 7) can be shared for several applications, since the same technological foundation is used for the automotive and connectivity application with specific adjustments.

Table 7 describes the applications, core process technologies and system requirements for automotive connectivity market segment.

Applications	Core process technologies	System architecture /system requirement
ADAS, CCAM	FPGAs & ASICS, real time processing of complex data, MC with AI accelerators, most advanced CMOS process nodes, neuromorphic computing	"Reliability procedures, retransmission or redundancy" - enable self-healing (software update)
In cabin sensing	> 100 GHz (high resolution, small antenna/ module size	High resolution imaging with THz microwaves or infrared light (ToF technology), e.g. detection of persons on the rear seat (children) and are they wearing seatbelts
Automotive RADAR: Front facing ADAS applications like automatic emergency breaking, automatic cruise control	77, 79 GHz CMOS/SiGe radar chipsets and companion radar processors	Radar front end with multiple Tx and Rx chip (for imaging radar cascaded front ends) in conjunction with a radar processor
Automotive RADAR: Side facing ADAS applications like blind spot detection, lane change assist	77, 79 GHz CMOS/SiGe radar chipsets and companion radar processors	Radar front end with multiple Tx and Rx chip in conjunction with a radar processor
Sensorfusion (radar, ultrasonic, lidar, camera…)	Stacked imager-digital processes, powerful CPU, high data-rate (<100Gbps) interconnected bus	AI based edge-processing, Transmission of uncompressed data from sensors to CPU

A SWOT analysis of the European strategic position and potential in the "Automotive connectivity" market with respect to compute and store is summarised as follows.

Strengths

- Automotive qualification & design experience to build robust & reliable systems
- Design of specialised MCUs
- Software tools for FPGA design (Siemens EDA)
- For Radar: MMIC in CMOS & SiGe mm-wave design capabilities
- Europe is strong in power converter (for connectivity)
- Focus on energy efficiency (GaN, SIC available)

Weaknesses

- High automotive qualification requirements slow down T2M
- Large scale digital chip manufacturing: No highly integrated CMOS designs
- No European actor in CPU or FPGA missing semi-conductor technology for high frequencies (III/V)
- Missing competence in MPU in Europe

Opportunities

- IC design and integration capability in Europe
- AI Computing, ML, and neuromorphic computing
- Standardisation facilitating the interoperability of economic operators in the value chain and provide technical certainty.
- For higher frequencies, higher performance needs to build on our capabilities for harsh environment
- AI based approaches to design process -> T2M acceleration, esp. for V&V

Threats

- Competitors from outside non-EU automotive community (e.g. Tesla, Google car, Apple car)
- Automotive RADAR EU has no highly integrated CMOS single chip radar system (US only offering)
- Radar interference: Digital radar at 77GHz threat to FMCW (wide adoption and EU strength)
- Tough competition from outside EU in LIDAR technology

4.3.3 Identified key strategic actions

Based on the previous analysis in Subsection 4.3.2, COREnect recommends the following key strategic actions in a short-term, mid-term and long-term, addressing the strategic focus area of "Sense and Power". A summary is first provided in Table 8 and more detailed descriptions are discussed in Subsections 4.3.3.1-3.

#	Short-term (<2026)	Seg. #1	Seg. #2	Seg. #3	Seg. #4	Sus.	Tru.
Rs.3.1	Improve advanced acoustic voice pickup unit		X	X	X		
Rs.3.2	Strengthen the European position in wide bandgap devices	X		X		X	X
Rs.3.3	Develop AI cores for edge sensors			X		X	X
Rs.3.4	Further research on power supply for micro sensors (Si batteries, micro solar panels, integrated batteries, energy harvesting technologies)		X	X		X	
Rs.3.5	Improve wireless charging		X	X			
Rs.3.6	Develop a power management strategy in cars				X		
Rs.3.7	Solve radar interference with increase of radar adoption in vehicle fleet				X		
Rs.3.8	Develop cost-efficient high data-rate interconnects			X	X		
Rs.3.9	Research on alternative methods for the human-machine interface		X	X	X		

	Mid-term (2026- 2030)						
Rm.3.1	Research on RF communication for energy transfer over distance			X		X	
Rm.3.2	Improve machine learning and neural network algorithms			X		X	X
Rm.3.3	Improve localisation for IoT in an industrial context	X		X			
Rm.3.4	Develop alternative solutions for power distribution			X			
Rm.3.5	Develop higher processing power for imaging		X		X	X	X
Rm.3.6	Develop datacentres on wheels, connected with edge computing				X		
Rm.3.7	Expand radar sensing in higher frequencies (SiGe leads the way, CMOS needs to follow)				X		
Rm.3.8	Develop safe and secure remote sensors			X			
Rm.3.9	Develop effortless and permanent interaction with Internet via 6G with new human-machine interfaces		X	X	X		
	Long-term (2030>)						
Rl.3.1	Further research on power over fibre			X		X	
Rl.3.2	Develop highly integrated THz imaging				X		
Rl.3.3	Research in LIDAR technology		X		X		X
Rl.3.4	Develop sub-THz concept for high data-rate communication combined with high-resolution sensing	X	X	X	X		

Table 8

Summary of Identified key strategic actions where Seg. #1 corresponds to “Connectivity Infrastructure” market, Seg. #2 corresponds to “Consumer Grade Connectivity” market, Seg. #3 corresponds to “Industrial Grade Connectivity” market, Seg. #4 corresponds to “Automotive Connectivity” and Sus. and Tru. denote sustainability and trustworthiness respectively.

Rs.3.1 Improve advanced acoustic voice pickup unit

Nowadays, the acoustic voice as input is already widely used in smartphones, IoT devices, cars, etc. To communicate with others, recoding or controlling the devices connected to the system. In the lifestyle domain, key is to generate ease of use for the end user and deliver an enhanced user experience. Crucial points are for example a good calling experience without background noise and smart voice recognition that processes the words, meaning, and context accurately and correctly.

As of today, the voice pickup units within consumer devices still deliver many implications that prevent an optimal user experience, although the bandwidth to transmit the voice is already there. With the deployment of 5G and 6G, virtual human interaction will gain even more importance and new business models and applications will complement the already plentiful possibilities for voice input. In short-term, an improvement of the advanced acoustic voice pickup unit is needed to eliminate the acoustic implications. Thus, research and innovation are needed in the fields of bone conduction sensors, acceleration sensors, and other related sensor technologies.

Rs.3.2 Strengthen the European position in wide bandgap devices

Concerning power distribution, wide bandgap (WBG) devices pay a key role by improving efficiency and possibility to reduce the volume and/or increase the power density. High voltage direct current (HVDC) buses provide the possibility to reduce power consumption and to adopt smart power management solutions thanks to the availability of power converters and metering sensors. High density and high efficiency are key parameters for such systems and WBG devices are necessary to boost the performances. Target is to strengthen the European position in wide bandgap devices exploiting the know how built so far by many European companies. WBG devices are also key to the communication network by improving the efficiency of the power amplifiers. GaN, SiC are the most important materials for power distribution, while GaN and InP is crucial for communication. Thus, research should be continued in this sphere to find new solutions (cost reduction, etc.), improve reliability and increase performance. On the other side, support for manufacturing and the development of new applications should be focused.

Rs.3.3 Develop AI cores for edge sensors

Widespread use of IoT device and sensors generate a huge amount of data. Direct transmission of this amount of information is not feasible and contributes to the power demanded for the communication. One key technology which helps reducing the amount of transmitted data is AI pre-processing. An edge AI processor embedded in the sensor identifies the useful information to be transmitted, therefore reducing the required rate. Due to the intrinsic discontinuous nature of IoT sensor operation, neuromorphic circuits allow minimum power consumption. Memristor-based analogue or mixed-signal AI processors do not require large amount of digital processing, therefore huge investment in small IC technology nodes is not necessary, but investments are necessary for research to identify new architectures and new solutions for the AI cores.

AI technology not only supports the large deployment of IoT devices but is also fundamental for the optimised management of telecommunication and power grids. By properly monitoring the network, AI processors can consider large number of variables and optimise the performances despite the high level of complexity. Core AI processors rely on small technology nodes, which are not readily available in Europe. Short term target should be strengthening collaboration with companies outside Europe on one side, while on the other side it is necessary to create a solid know-how on how to implement suitable algorithms for these tasks. Machine learning, neural network training and training dataset identification are some of the key critical intellectual properties needed. Anyways, for a European strategy to build small technology nodes in Europe, building core AI processors is a long-term strategic target.

Rs.3.4 Further research on power supply for micro sensors (Si batteries, micro solar panels, integrated batteries, energy harvesting technologies)

The current Si batteries in use rely on materials which are difficult to extract and recycle. Therefore, the main focus should be the development of new chemistries based on readily available or widespread materials. With new battery solutions, the carbon footprint can be reduced and the recyclability improved. But not only the chemistry industry, but also the microelectronics industry needs to step up to guarantee proper functionality of charge, discharge, as well as optimisation.

At short term, solar powered devices are likely the first to be mature enough to enter a large market, as prototypes of solar powered Bluetooth enabled sensors are now state of the art. However, to be able to enter the consumer market, some progress is still required in terms of cost (ultra-low power is expensive) and reliability. Most early application will likely be on building automation.

As the communicating systems market is booming, the role of energy harvesting (EH) will be growing. Connected devices are going to be used more and more in several fields such as healthcare, wearable, home automation, etc. The Internet of Things (IoT) market grows considerably leading also to the boom of the connected devices, and so highlighting the importance of energy needed to supply them in view of the limitations of current battery technology. In this particular case, we are focusing on small, connected devices with low power consumption below a few mW (or even a few tens of μW). The objective here is that local energy harvesting will substitute battery-powered devices and eliminate the high demand in energy for battery manufacturing and distribution logistics. Therefore, self-powering systems for small IoT nodes must be developed.

Different wasted energy sources can be exploited and converted into electricity: sun or artificial light, heat, RF power (intentionally transferred), mechanical movements, vibrations, etc.. Moreover, this converted energy needs to be used and transferred wisely to sensors, microcontrollers or other electronic components included in the system. Thus, power management circuits and energy storage devices also become essential elements. In this roadmap report, we have assessed several promising technologies for EH including photovoltaic cells for outdoor/indoor light EH, thermal energy harvesting, and mechanical EH based on three concepts: piezoelectric materials, electrostatic and electromagnetic energy conversion, and RF energy harvesting/wireless power transfer. Targeting EH technologies with low fabrication cost, with high efficiency, and without toxic/rare materials is the main challenge. Adding flexibility and/or transparency is also an increasing demand for compatibility with wearables applications.

Rs.3.5 Improve wireless charging

Regarding wireless charging, currently there is mostly inductive charging in use. It uses electromagnetic induction to provide electricity to portable devices and is used in vehicles, consumers or medical devices. Short-term goals would be improved efficiency in the inductive coupling, with increased distances and compatibility with multiple pieces of equipment. Higher frequencies from 7 to 13 MHz also need further research. To sum up, research in those areas, as well as collaborations among different companies from the communication and electronics domains, are desired.

Rs.3.6 Develop a power management strategy in cars

The power management in cars should include low power dissipation, a small form factor, heat management friendly design, strong electromagnetic isolation and cost-effective system design. Today, it is not possible yet to introduce large-scale MIMO radars in commercial cars from a cost and form factor perspective.

Rs.3.7 Solve radar interference with the increase of radar adoption in vehicle fleet

Short term solutions need to address the current technology platform of FMCW based 77GHz automotive radars. Different mitigation approaches are currently being looked at by the industry and research communities. Managing radar interference is an important factor towards high quality target detection and increased safety in automotive context, especially in urban scenarios, gets more and more important as more vehicles are equipped with radars. Current radars are not resilient to interference. Addressing radar-radar interference is enabled by e.g. code, frequency and spatial orthogonality of the radar waveform. This requires incorporating MIMO communications technologies into radar sensors by using different modulation approaches, for example, phase and amplitude modulation allows creating versatile waveform shapes optimised for interference robustness at the cost of stringent requirements for the mm-wave front-end (linearity, band-width and isolation), or even PMCW instead of FMCW, or with their combinations thereof.

Rs.3.8 **Develop cost-efficient high data-rate interconnects**

The demand for greater I/O bandwidth in telecom systems and data centers is increasing exponentially caused by the explosive growth of network traffic. The same is the case in cars as they are transforming from simply a mode of transport to a mobile personalised-information hub. Therefore, wireline data communication bandwidth must also grow exponentially to avoid limiting the performance scaling of these systems.

By increasing the data per pin or cable of various electronic devices and systems, such as backplanes, rack-to-rack designs, local area networks and the data-bus in cars, wireline input–output (IO) has fueled incredible technological innovation in electronic devices and systems. The data rate per pin has approximately doubled every four years across various IO standards, ranging from double data rates (DDRs) to graphics and high-speed Ethernet.

In part, this incredible improvement is enabled by the power–performance benefits of process technology scaling. However, sustaining this exponential trend for IO bandwidth requires more than just transistor scaling. Significant advances in energy efficiency, channel equalisation, and clocking must be made to enable the next generation of low-power and high-performance systems.

Therefore, continuing to aggressively scale IO bandwidth is essential for all the identified domains like Connectivity Infrastructure, Consumer Grade Connectivity, Industrial Grade Connectivity and Automotive Connectivity.

The trade-offs between bandwidth, power, area, cost, and reliability are extremely challenging. For example copper-based electrical links are bandwidth limited caused by the skin losses and require complex circuits for equalisation and coding. In optical links, for short distance, their complexity and cost for the E/O and O/E conversion devices and the chip-to-fiber assembly is an issue. Therefore, also alternatives like THz-waves over plastic fiber should be considered for this application. The latest reported achievements in terms of data-rate and distance are indicating, that terahertz-over-plastic has the potential to compete with existing Cu-based and optical technologies used in high-throughput data interconnects.

Rs.3.9 **Research on alternative methods for the human-machine interface**

The voice is the most immediate and efficient communication tool of the human being. Bone-sound detection enables almost complete differentiation between spoken sound, i.e. a message one sends, and ambient noise and received messages. It is expected that this type of human-machine communication will enable a disruptive simplification of voice control. Increased research to improve existing VPU MEMS devices and algorithms, as well as the development of new sensor principles, in combination with smartphones, smart speakers and 6G, can lead to a natural, omnipresent and efficient interface with the Internet.

Rm.3.1 Research on RF energy transfer over distance

In the long run, it will be possible to transfer power over the air instead of a cable, e.g. with beaming to power specific, distant equipment. To improve wireless energy transfer, low-cost and energy-efficient approaches for beam re-focusing based on reconfigurable meta-surfaces in mm-wave and THz bands will be used to increase coverage of future 6G networks. Additionally, to further increase the number of sensors, novel mm-wave battery-less and chip-less IoT solutions will be considered to perform measurements and send back information using energy generated by interrogating mm-wave base stations able to focus antenna beam (Power over Air – PoA).

Rm.3.2 Improve on Machine Learning and Neural Network Algorithms

To speed up the training of the neural network and develop new architectures to address multiple problems with lower cost and lower power-consumption, ML and neural network algorithms should be improved. This can be achieved through the development of new applications, improving existing ones and setting a strong research focus. Besides, unsupervised ML with the automated definition of the training set is a promising field. Overall, the main target is efficiency improvement and flexibility.

Rm.3.3 Improve localisation for IoT in an industrial context

Acquiring the real-time spatial-temporal information of manufacturing resources is an essential part of an efficient operation in factory logistics. Localisation via IoT (Bluetooth low energy (BLE), ultra-wideband (UWB) and radar contributes to this functionality.

Rm.3.4 Develop alternative solutions for power distribution

With the large deployment of the 5G network, the challenge to limit power demand becomes crucial. This possible increase could have severe consequences on the generation of the electrical power as well as on the power distribution grid with negative impact on the environment. National and international policies drive a shift from fossil fuel to renewable energy sources. Most of these renewable sources have intermittent behaviour and availability: for example, solar energy is available only during daytime, wind and tide energy depend on environmental variability. On the other side, the radio network must be operative at all times. For this reason, it is necessary to introduce algorithms, models, and converters to optimally exploit these heterogeneous sources and, in combination with suitable energy storage, make power available as necessary.

On the distribution side, integration with energy storage elements is fundamental to guarantee stability of the power grid. In this case AI-based scheduling algorithms can be employed to optimise exploitation of the different power sources based on availability and demand and cope with local failures or critical conditions. Multi-input, high-efficiency and high-density converters need to be developed for the user side, to allow the user equipment to seamlessly switch from one source to the other.

Rm.3.5 Higher processing power for imaging

Healthcare consumerism is on the big rise and continuously gains complexity with all the wearables an internet-connected IoT health devices, that create huge amounts of data. One of the next big Megatrends will be the individual surveillance of the body, where the end user has the ability to track and analyse bodily functions and take preventive measures with the support of technical devices. Medical imaging, coming from CT scanners and mammography devices, is now benefiting from detailed resolutions with less noise and artifact by producing 3D images. The evolution in networking, computer power and software has made the evolution possible to process those large datasets. Introducing this technology into the consumer market will bring many new business opportunities and move healthcare consumerism to a new level. The bandwidth of 6G allows the data masses generated by consumers to be transferred. Further research on computing power is needed to ensure fast data processing by the algorithms. Also, related sensors (THz, photoacoustic, ultrasound) and the integration of smart devices and wearables related to the field of healthcare consumerism need further research efforts.

Rm.3.6 Develop datacenters on wheels, connected with edge computing

In the future, Internet-of-Vehicles (IoV) will become a defacto standard. It represents a fundamental shift in how we view and use vehicles, from simply a mechanism to move from place to place to an automated device and data centre on wheels that is integrated not only into our lives but into the other cars, pedestrians, and infrastructure around it. Thereby, the role of electronics controllers in vehicles is evolving from distributed domains to interconnected computing and server platforms. This has consequences for how you build the architecture, especially while the importance of security in automotive products is steadily growing, e.g. to prevent unauthorised access from and to the in-vehicle network, provide secure booting of multi-stakeholder software to ensure the device only runs unmodified software from a trusted source, or allow firmware over-the-air.

In the future, quantum- secure security features will be needed to keep the radar system secure. Overcoming these technical locks requires a paradigm shift from the current radar system

Rm.3.7 Expand radar sensing in higher frequencies

Modern commercially available SiGe-based BiCMOS processes offer bipolar transistors with transit frequencies (ft) > 300 GHz and transconductance values of more than 200 mS/µm² and CMOS nodes down to 55 nm which allows to create complex mixed signal RF systems. These technologies already open the way towards applications in the sub-THz range. Highly scaled CMOS devices still do not fully achieve the RF performance of state-of-the-art SiGe devices with respect to transit frequency, breakdown voltage (RF power handling capabilities) and noise properties. As an alternative BiCMOS technologies, which are very well suited for medium chip complexity due to their CMOS nodes down to 5 nm has superior RF performance at relatively low mask cost. For this reason, BiCMOS still is and will be in the future a leading technology when it comes to mm-wave and sub-THz range communication and sensing front-end systems.

As Si based power generation in the sub-THz still is still mainly based on RF multiplier and power combining architectures, which offer limited efficiency and require substantial die area, the increase of the SiGe devices transit frequency ft at reasonable breakdown voltages around 1.5 V is an important precondition to truly push silicon-based systems into the THz range. Higher frequencies offer higher achievable resolutions. Coming from 24GHz systems, 120-140GHz radars are being explored for in-vehicle passenger monitoring and gesture recognition applications. Use cases outside the vehicle with a need for extreme resolutions need further exploration. The aim is to increase angular, range and velocity resolution. Classification, localisation, mapping, and segmentation cannot be performed sufficiently by current radars, thus, a high resolution aids the implications. It radiates more energy on the scene and improves link budget. This allows for better detection, especially for vulnerable road users such as kids and cyclists in presence of large obstacles.

While SiGe transceivers at higher frequencies provide benefits in the RF design, their lack of integration capabilities will lead CMOS-based designs to catch up into the sub-terahertz frequency spectrum promising highly integrated radar systems in package at a cost advantage. This requires substantial innovations in the CMOS space to overcome the RF performance advantages of SiGe. Introducing CDMA multiplexing with a PMCW waveform allows what is referred to as digital sensing. Important is also to focus on large-scale integration of the mm-wave transceiver and baseband processor.

Rm.3.8 Develop safe and secure remote sensors

Sensors are being widely utilised in the automotive, connectivity, industrial and consumer domain. For IoT devices, a lack of clear standards for cybersecurity and built-in security makes the device vulnerable for attacks. In embedded devices, the security vulnerabilities can occur in the implementation, design, and deployment. Regarding sensors, the underlying hardware often lacks built-in security features like insufficient encryption due to limited processing power and storage. By adding a few basic capabilities, including secure boot, secure firmware update, secure communication, data protection, and user authentication, the security of any device can be significantly increased. Only in-built security in the devices themselves can ensure that IoT-connected sensors and sensing systems will be protected from cyberattacks. Future research efforts are needed in the fields of encryption (e.g. post-quantum encryption). Furthermore, even if data and its communication is secured, the ethical question of who owns the data and should benefit from the exploitation has to be answered by society.

Rm.3.9 Develop effortless and permanent interaction with Internet via 6G with new human-machine interfaces

The human-machine interaction changed from tactile input devices to speech/audio and gesture sensors. The next step will be neural interfaces, neuromorphic sensing, and highly adaptive machine learning techniques. The efficient interactions with kinetic and physiological signals from human body through the fusion of tactile sensor and neural electronics with 6G infrastructure will bring a revolution to Human-Machine Interfaces, wearable electronics and biomedical applications. Not only for the sake of Human Machine Communication but enabling new dimensions in Human-Human Communication.

RI.3.1 Further research on power over optical fibre

For the sake of safety and simplicity, the transmission of power over fibre allows to transmit data and power through one optical fibre or fibre cable. The optically transmitted data can be modulated and the power from the light extracted to the power equipment. This brings several benefits, e.g. the replacement of bulky transformer systems with isolation and protection equipment, that can be left out by using optical power. Also, optical delivery avoids electromagnetic interference and there is no danger with explosive materials.

Research is needed on materials to improve the optical power's efficiency and capability to transfer power. A research aspect should be application-specific solutions for low-power equipment in short distance.

RI.3.2 Develop highly integrated THz imaging

A long-term aim is to develop a path towards THz imaging crossing radar, camera and lidar boundaries to enable a significantly higher resolution of the automotive environment. Integrated THz antennas will have to be combined with AI for radar signal processing, coded-radar for interference suppression in super-dense environments, distributed high-resolution automotive radar, high-speed wideband, high-performance analogue-digital converters (ADC) and chopping with high-speed 1/f noise reduction techniques.

RI.3.3 Research in LIDAR technology

It is a broadly accepted notion that the lidar is a must-have technology to transform cars into fully autonomous vehicles able to operate on city streets. However, lidars technology is not yet mature and is very expensive. It is expected that we are at the beginning of big changes coming to lidar. Citing the different approaches to scanning technology, lidars can be divided into five categories: multi-channel macro-mechanical scanning, other mechanical scanning, MEMS lidars, optical-phased array lidars, and flash lidars. In the leader research community, considering the number of publications, it seems that lidars using optical-phased arrays, as the most relevant concept for the future. With no moving parts, they can be even cheaper and smaller compared to the other competing concepts. Just flash lidars seem to be simpler to make but their range is less than that of MEMS lidars or optical-phased arrays.

Regarding the future of lidar, there is one point to consider, namely the advancement of competing technologies. While automotive lidar technologies continue to advance, the same is true of other sensor technologies used in ADAS and autonomous vehicles. For one, automotive radar's imaging capabilities are getting better by using beam steering. Similarly, vision processors combined with AI are also improving. They help cameras detect and classify objects, allowing them better understanding of three-dimensional space. Today it's too early to determine which technologies will prevail in autonomous cars. However, redundancy between sensors will be necessary for ADAS cars and robotic vehicles and lidar will be part of it, to reach their potential.

RI.3.4 Develop sub-THz concept for high data-rate communication combined with high-resolution sensing

The motivation to pursue sub-THz Wave networks remains the same as it always has - the need to support the increasing demand for data. As large numbers of people congregate, the data consumption spikes and networks often strain to keep up. There are 'off-load' strategies in 4G (mostly Wi-Fi-based solutions) and 5G (ultimately using mm-wave technology) and for 6G it is foreseen to move to the sub-THz spectrum.

The purpose of the wide bandwidth sub-THz frequencies is to provide very high data rates at low cost, and in addition, add new services such as ultra-high-resolution positioning and sensing (with cm range resolution). Active sensing, where the sub-THz signals are transmitted solely for the purpose of sensing is also possible, allowing a base station to act as a radar system in addition to serving the communication needs of an area. This can be used to build and continuously update a map of surrounding areas to, for example, detect changes in road traffic or set off alarms if a person enters a restricted area in a factory hall. Reusing cellular systems for sensing can provide more cost-efficient sensing compared to the dedicated systems specifically deployed for sensing only. Further, by using data analytics on the radio signals received it is possible to sense and estimate quantities impacting the radio propagation (like rain or snow for weather forecast).

4.4 HIGH-LEVEL RECOMMENDATIONS AND COMMON STRATEGIC ACTIONS ACROSS STRATEGIC FOCUS AREAS

Beyond the strategic actions proposed in each strategic focus areas, transversal actions are analysed and defined in COREnect deliverables D2.2 Consolidated vision and requirement report and D3.7 Core Technologies Development Recommendations and Guidelines, as key enablers and complement measures to secure and strengthen the proposed strategies.

For the completeness of roadmap, a summary of high-level recommendations and common strategic actions across "Compute and store", "Connect and communicate" and "Sense and power" are presented in the following. More details of analysis and recommendations will be found in D2.2 and D3.7.

4.4.1 A summary of high-level recommendations to build a stronger position on microelectronics and future connectivity

Table 9

A summary of high-level recommendations on R&I investment requirements analysed in D2.2

#	High-level recommendations on R&I investment requirements
Rh.1	Create and strengthen concrete actions for market growth through technological excellence to build economic sustainable sovereignty and resilience. • Ensure a level playing field of Europe with the rest of the world and within Europe amongst the different Member States, staying competitive and growing or keeping market leadership;
Rh.2	Control strategically over several critical and/or strategic parts of the value chains and build up value networks instead of value chains • Promote more and more cooperation on horizontal levels throughout different value chains.
Rh.3	Streamline further strategic priorities between Europe, Member States and Industry including the definition of top-priority ambitions • Coordinate activities for the creation of European roadmaps and priority topics for research and innovation as SRIA's from KDT and SNS and create enough momentum and critical mass to achieve excellent results and translate longer term technological ambitions into market success.
Rh.4	Enhance ecosystems of large enterprises, SME's and RTO's both in horizontal competence areas as in vertical value chains • Promote joint strategic developments amongst semiconductor companies (e.g. "Airbus of RISC-V") and between OEMs & semiconductor companies (e.g. joint common domain-specific processor & platform developments) • Set-up "Fast-Track initiatives"' within European and national cooperation programs for smaller-scale key advancements in specific technological areas • Support an EU open-source computing hardware ecosystem, to lower the entry costs for new chip designs. • Spread innovation beyond Horizon Europe. "Innovation should be spread across the entire EU framework of regional policy, agriculture, and structural funds", says MEP Maria da Graca Carvalho.

#	High-level recommendations on R&I investment requirements
Rh.5	Improve further the efficiency of the process and administration of European research programme • Shorten the time between proposal submission and start-of-the-project • Reduce uncertainty in financial support for some instruments and unclarity on the priority of technical expert proposal evaluations versus national economic strategic preferences.
Rh.6	Recommend a dedicated call for a strategic call on micro-electronics for 6G with all involved key stakeholders in Europe within the KDT framework.
Rh.7	Promote the role SMEs in the European microelectronics and connectivity ecosystem • Strengthen the interaction between corporate companies, research organisations, and SMEs. • Enable matchmaking between European SMEs, and with other European stakeholders.
Rh.8	Create the conditions for the emergence of one or more European champion(s) from microelectronics and connectivity domains • Support the involvement of SMEs on Horizon Europe Programmes in topics related to components for future connectivity systems • Encourage corporate participation in targeted investments in Venture Capital (VC) funds that finance early-stage SMEs developing advanced connectivity applications • Provide more support to SMEs facing heavy investment after the first patent is filed and/or the first solution is being developed. • Create a dedicated co-investment platform focusing on components for 6G, again involving corporate VCs from microelectronics, telecoms, and verticals • Create pan-European sandboxes, a one-stop shop where a company would apply for approval and would be automatically eligible to offer products and services throughout the EU market

Table 10

A summary of high-level recommendations on strategic actions for political support analysed in D3.7

#	High-level recommendations on strategic actions for political support
Rh.9	**Speed up 5G deployment in Europe and define a consistent EU spectrum policy** • Support and promote the initial stages of 5G deployment, especially in the sub-7 GHz spectrum, is recognised as a key issue in Europe • Implement a coordinated policy across all state members in the 2022 – 2030 timeframe, with a clear leadership and long-term vision
Rh.10	**Support Europe's contribution to standardisation activities** • Implement tax incentive on standardisation activities to support European companies to dedicate more resources to the topic • Define clear objectives on standardisation activities to European research institutes to reinforce actions of the European industrial actors
Rh.11	**Secure access to leading edge CMOS technologies** • Establish key partnerships at European level with leading foundries and fund a yearly shuttle to secure the access to advanced CMOS technologies to selected European universities and research institutes • Set up a dedicated organisation managing the access to these technologies as well as the access to dedicated CAD environments using cloud solution
Rh.12	**Take measure to boost the European micro-electronics community** • Consider elements from the Chinese approach such as specific investments and incentives as well as greater focus on talent recruitment regarding IC design • Create specific talent attraction programs targeting international graduate students as well as experts and through a greater focus on the required competencies during university education
Rh.13	**Adapt policy to geopolitical tension** • Strengthen political will and export control tools are here mandatory to define appropriate policies and regulations enabling to defend the freedom that technology leadership can bring to Europe
Rh.14	**Define and enforce new regulation aligned with European values and ethical principles on privacy, security and sustainability** • Enforce stringent power efficiency regulation on the European market, speeding the adoption of innovative and clean technologies developed in Europe • Promote research on the environmental impact of ICT and sector-wide net zero commitment, enforced through incentives and compliance mechanisms, application of constraints on consumption for the end-user and industry and a strategy towards global alignments, enforcing sector-wide climate target compliance.
Rh.15	**Strategic Infrastructure program lead by state members and the commission** • Support financially the deployment of state-of-the-art broadband infrastructure (both wired and wireless) targeting a clear timeline, coverage, and data rates (defined at political level) to ensure best in class services availability across Europe. • Support the raise of European cloud solution providers by allocating public contracts on sensitive areas (such as eHealth, defence, government agencies, etc.)

4.4.2 A summary of common strategic actions across three strategic focus areas

Table 11

A summary of common strategic actions across three strategic focus areas analysed in D3.7

#	SHORT TERM (<2026)
Rc.s.1	**Maintain & strengthen Europe position on semiconductor manufacturing equipment** • Promote collaboration as the key to success, as far as a given area can provide specific products and technologies that other regions need • Secure Europe's relevance in the global semiconductor ecosystem by increasing the capabilities and performance of European products and technologies that others rely on, e.g., semiconductor manufacturing equipment
Rc.s.2	**Strengthen EU's position on mature technologies** • Provide the appropriate insensitive for the installation in Europe of state-of-the-art 300 mm manufacturing facilities dedicated to those mature technologies. • Support the R&D activities to develop the next generation of associated technologies (SiGe BiCMOS, FD SOI, RF SOI, GaN, BCD, POI RF Filters, …)
Rc.s.3	**Strengthen Europe's position on EDA solution market** • Support start-up and SMEs to develop innovative EDA tools and IP solution leveraging AI and Machine Learning (for example through dedicated EU programs). • Enable M&A activities in the EU by securing dedicated funds to ensure a dynamic European EDA ecosystem.
Rc.s.4	**Support the development of open hardware and software ecosystem** • Provide more R&D funding to open-source software and hardware programs, in particular targeting SMEs, to support and accelerate the creation of open-source software and hardware technologies in Europe • Implement tax incentives on activities contributing to open hardware and software ecosystems to incite the involvement of European companies
Rc.s.5	**Support the development of components/HW technologies catering needs of connectivity markets** • Allocate funding for projects to work on the areas that are critical for European industry leadership in 5G/6G. • Establish communication links among the KDT and SNS JUs and coordinate the development in these two communities, ensuring synergies and strong demand-supply correlations in European R&I scene.
Rc.s.6	**Support the development of platform chipsets enabling a wide range of applications on a single modem** • Include more interactive teaching and hands-on activities through lab projects using open-source software and hardware solutions • Improve the collaboration with STEM industries to simulate the cohesion and alignment between education and industry • Provide dedicated funding e.g., through scholarships, to make STEM education accessible for everyone • Provide easier admission to universities for non-European students by offering more English programs and establish European agreements promoting the issue of student and working visas in the STEM field.

Rc.s.7 Improve EU technical university attractivity and admissibility to increase the pool of talents available in EU

- Promoting vertical industry alliances and fostering common interests across sectors, increasing demand on platform chipsets developed in Europe.
- Providing R&D funding and state-aid support to platform chipset design programs, building European capability and ecosystem in this area.

Rc.s.8 Create acceptance for sensitive data sharing

- Evaluate sensor data reliability with a confidence level to identify a defective device into a subset of devices.
- Track performance thanks to rapid monitoring and feedback systems, even allowing remediation actions to enable self-healing wherever possible (e.g. software updates).

MID-TERM (2026 - 2030)

Rc.m.1 Increase IC design capabilities in digital and analogue to ensure a sufficiently large pool of resources in EU

- Support existing academic institution focus on analogue design with appropriate funding to secure Europe track of record of excellence in education and research in this field.
- Strengthen digital IC design educational programs to improve Europe's pool of resources and secure the capability to address complex SOC design in the future.
- Stimulate research institutes to organise advanced technical training courses to extend the expertise in local and international industry.

Rc.m.2 Develop heterogeneous integration technologies (2.5D/3D) in the EU to address complexity and performances challenges in an innovative way leveraging EU mature technology strength

- Allocate more R&D funding to collaborative programs dedicated to heterogeneous integration and advanced packaging (a flagship project could help to federate and improve the focus on those key topics).
- Upgrade European research facilities dedicated to heterogeneous integration and advanced packaging, and consequently develop new pilot lines to speed up the transfer of developed innovation to the industry.

Rc.m.3 Establish a European fabless ecosystem developing complex SOC achieved in leading edge CMOS technologies to serve the domestic and international market

- Facilitate investments in European fabless SMEs to enable a dynamic European ecosystem.
- Provide more R&D funding to IC design programs led by SMEs and start-ups targeting key digitalisation programs led by the Commission.

Rc.m.4 Deploy open hardware and software ecosystems targeting safety and security contexts

- Integrate open-source software and hardware technologies and their communities not only into European research and innovation policies, but also into general policy frameworks, such as the European Green Deal and European industrial strategy.
- Enforce the public sector to favour the procurement of open-source hardware and software technologies instead of proprietary solution to reduce the total cost of ownership, avoid vendor lockin and thus increase Europe digital autonomy.

Rc.m.5 Establish leading edge technology source in Europe

- Support the European semiconductor manufacturer ecosystem with long period incentives to build more advanced logic fabs to address their key end markets' (automotive, industrial, wireless infrastructure, ...) long term needs.
- Attract industry frontrunners (TSMC, Samsung or Intel) with strong incentives to establish an advanced logic fab in Europe to serve both its industrial and automotive current players (as done by Japan with TSMC 28/22 nm and 16/12 nm Fab in Kumamoto[60]), as well as developed European fabless ecosystems (which may require more advanced nodes).

60 https://english.kyodonews.net/news/2022/02/80b71fff7c72-tsmc-to-increase-investment-in-chip-plant-in-japans-kumamoto.html

	LONG TERM (> 2030)
Rc.l.1	Enable the development of next generation derivative technologies to secure Europe leadership in the long term • Support the development of InP on Si technologies to enable innovative (sub-) THz and optical applications. • Strengthen advanced packaging activities to enable innovative heterogeneous integration schemes leveraging Europe's mature technology portfolio.
Rc.l.2	Enable European Cloud solution & service providers to address domestic and international markets • Build a common and unified digital market by establishing common regulation rules to enable more start-ups to scale up and help European champions to emerge. • Set up an innovative financing strategy, for example by enabling investors to create European funds in a simple and standard way to orientate European savings towards risk and innovation, to bridge the current venture capital gap with the US and China.
Rc.l.3	Strengthen leading edge technology source in Europe • Support the European semiconductor manufacturer ecosystem with long period incentives to build advanced logic fab able to compete with foundry leaders (leveraging the technology R&D development performed in Europe). • Attract additional industry frontrunners (namely TSMC and Samsung since Intel has already announced a new Fab in Germany near Magdeburg) with strong incentives to establish advanced logic fabs in Europe and enable a resilient and competitive supply chain for European Fabless ecosystem.

05 CONCLUSION AND THE WAY FORWARD

The two-year journey of COREnect has been an extraordinary one. Concluding its work in this roadmap, a new journey may begin to truly realise and deliver the common vision of telecommunications and microelectronics industries as well as build a strong position in those key digital technologies for Europe. Facing great uncertainties ahead in globalisation, geopolitics, post-pandemic economy and climate change, the road towards 6G and European digital sovereignty will be extremely challenging. COREnect consortium wishes this roadmap will not only provide a food for thoughts but more importantly a light, a compass, a map, and an action plan for Europe and all the related private and public stakeholders to find their way and succeed in this journey.

ANNEX A: ACKNOWLEDGEMENT

To come up a roadmap on microelectronics for future connectivity, as described in this document, the journey of COREnect industry roadmap started with organising three COREnect Expert Groups, addressing following three strategic focus areas:

- Expert Group #1 Compute and Store
- Expert Group #2 Connect and Communicate
- Expert Group #3 Sense and Power

The COREnect roadmap activities strongly relied on interactions with experts in the field. The COREnect consortium would like to express the highest gratitude to all COREnect experts. Without valuable contributions and feedback from those experts, the COREnect industry roadmap would not be possible here. Current members of the COREnect expert groups are listed below in Table 12 and Table 13.

In addition, COREnect would like to thank Hexa-X project, especially coordinator Mikko Uusitalo (Nokia) and technical manager Patrik Rugeland (Ericsson) for supporting bilateral workshop and providing contributions and feedbacks on 6G vision to the final roadmap, ensuring good alignment between the journey of COREnect industry roadmap and the most prominent early 6G research.

Last but not the least, COREnect consortium would like to devote special thanks to the European Commission DG CNET for the invaluable support and continuous encouragement, which makes the journey to the COREnect industry roadmap memorable and impactful.

Table 12

A list of COREnect Experts from within the consortium

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Imec	André Bourdoux, Björn Debaillie, Dimitrios Velenis, Eli De Poorter, Ingrid Moerman, Jan Craninckx, Jeroen Hoebeke, Johann Marquez-Barja, Mamoun Guenach, Michael Peeters, Nadine Collaert, Peter Ossieur, Piet Wambacq, Xiao Sun, Ilja Ocket
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NXP	Frans Widdershoven, Cedric Cassan, Domine Leenaerts, Jan van Sinderen, Javier Velasquez Gomez, Jean-Claude Loirat, Patrick Pype
Robert Bosch Stiftung Gmbh	Andre Guntoro, Andreas Schaller, Frank Hofmann
STMicroelectronics	Andrea Pallotta, Andreia Cathelin, Daniel Gloria, Frederic Gianesello, Pascal Chevalier, Pierre Busson, Raphael Bingert
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Table 13

A list of COREnect Experts from outside the consortium

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