

The growing importance of photonic terahertz systems

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Prof.dr.ir. Idelfonso Tafur Monroy
May 3, 2019

INAUGURAL LECTURE

The growing importance of Photonic Terahertz Systems

TU/e

EINDHOVEN
UNIVERSITY OF
TECHNOLOGY

DEPARTMENT OF ELECTRICAL ENGINEERING

INAUGURAL LECTURE PROF.DR.IR. IDELFONSO TAFUR MONROY

The growing importance of Photonic Terahertz Systems

Presented on May 3, 2019
at Eindhoven University of Technology

Introduction

Hello and thank you. I'm honoured by your presence here today, both in the auditorium and to those students and colleagues around the world who I know are watching on-line.

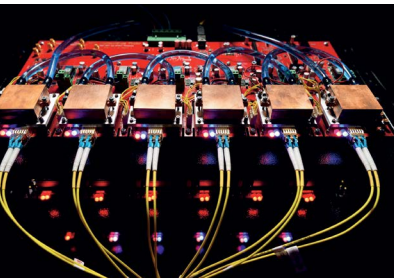
Thank you for the opportunity to explain. I'm also an outsider looking in. I am originally from Colombia. But all my scientific life has been spent abroad; in Russia, the USA, Sweden, China and Denmark. I completed a PhD in Eindhoven in 1999. But the reason for returning to TU/e in June 2017 was to be part of the next wave of research into light-based systems.

In this inaugural lecture I would like to discuss my preferred future for light-based technologies. I believe that cross-disciplinary teams are the key to Eindhoven University of Technology playing an essential role in solving several of the grand societal challenges. I hope to show that this process has already started. But it needs amplification well beyond the campus boundaries.

Some definitions of what we're talking about

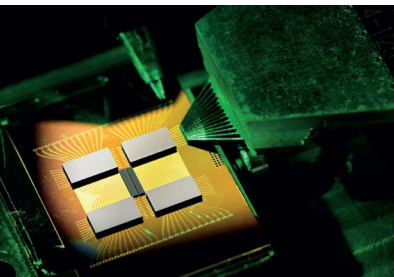
Let's start by defining photonics and its subset called integrated photonics. Rather than a standard technical definition, I find the following definitions insightful.

PHOTONICS



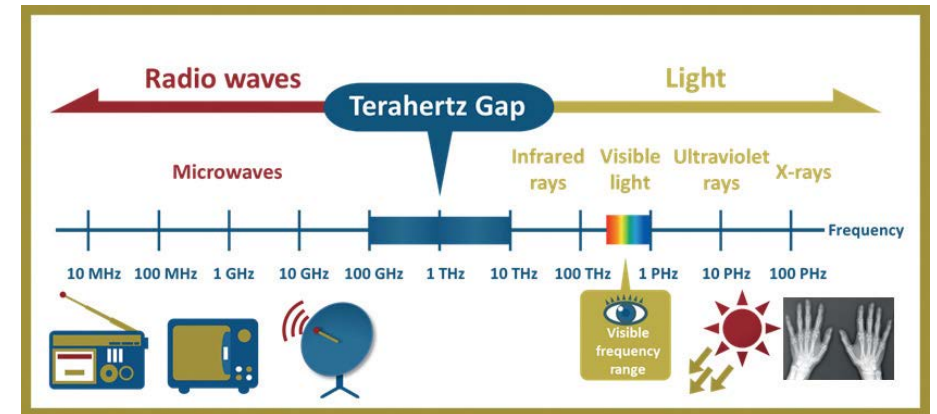
Photonics is the manipulation of light particles for the instantaneous transport of data. In essence, data is raw. It has not been shaped, processed or interpreted. It is a series of one's and zeros that humans cannot read. It is disorganised and inaccessible. Once data has been processed and turned into information, it becomes useable for society. It takes on context and structure. It becomes useful for businesses to make decisions, and it forms the basis of progress.

INTEGRATED PHOTONICS



Integrated photonics is the emerging suite of technologies where the manipulation of light takes place on a chip, so called Photonic Integrated Circuits (PICs). Building systems on a chip means that resulting products can be an order of magnitude faster, cheaper, lighter and smaller than conventional electronic/optical solutions whilst also being far more energy efficient.

Having defined Integrated photonics, let me explain why I am interested in using lasers to build terahertz communication systems and sensors. As you may know, scanning systems operating with X-rays have disadvantages. X-rays can cause mutations in our DNA. This ionizing radiation increases the risk of cancer later in life, especially for those exposed to them on a regular basis. For this reason, X-rays are classified as a carcinogen by the World Health Organization (WHO).



Terahertz gap denotes the frequency band in the terahertz region of the electromagnetic spectrum between radio waves and infrared light.

UNDERSTANDING THE TERAHERTZ GAP

In the search for alternatives to X-rays, physicists and engineers like myself have been looking at the properties of Terahertz radiation. This describes electromagnetic waves within the frequency range of 300 Gigahertz to 3 terahertz (THz). Wavelengths of radiation in the terahertz band correspondingly range from 1 mm to 0.1 mm which why it is sometimes known as the "submillimetre band". Terahertz radiation occupies a middle ground between microwaves and infra-red waves known as the "terahertz gap".

The technical challenge is that THz wave generation, ultra-sensitive detection, and manipulation is still in its infancy. The frequency of electromagnetic radiation becomes too high to be measured digitally via electronic counters. Similarly, the generation and modulation of coherent electromagnetic signals in this frequency range ceases to be possible by the conventional electronic devices used to

generate radio waves and microwaves. Approaching the THz gap from the infrared domain poses its own challenges too. Most equipment currently available is bulky, unportable and still too costly for mass deployment. But if we can solve this hurdle with new devices, then a wide range of possible applications presents itself. Let's outline a few examples.

SAFE MEDICAL SCANNING

The non-ionizing nature of THz waves makes it a much safer alternative to the use of X-rays for medical imaging applications. For instance:

- **Cancer imaging:** the distinct absorption and refraction lines within the 0.5 - 1.5 THz range of cancer tissue makes THz technology ideal for cancer imaging.
- **Dental imaging:** the non-ionizing features of THz technology enable a regular, fast, non-invasive scanning of the teeth with the use of a portable dentist probe, allowing for early detection of tooth decay during regular medical appointments.
- **Multi-spectral THz colonoscopy:** THz technology can be combined with the traditional camera approach for both a visual and multispectral THz examination, enabling the inner layers of the large intestine to be visualized as well.
- **Cosmetic applications.** THz imaging can be used to measure tissue hydration, melanin content, haemoglobin levels. For instance, you can test the levels of blood-sugar by simply pinching the skin and using a photonics enabled detector. That's a breakthrough for diabetes detection, especially in areas where dirty needles can spread deadly viruses.

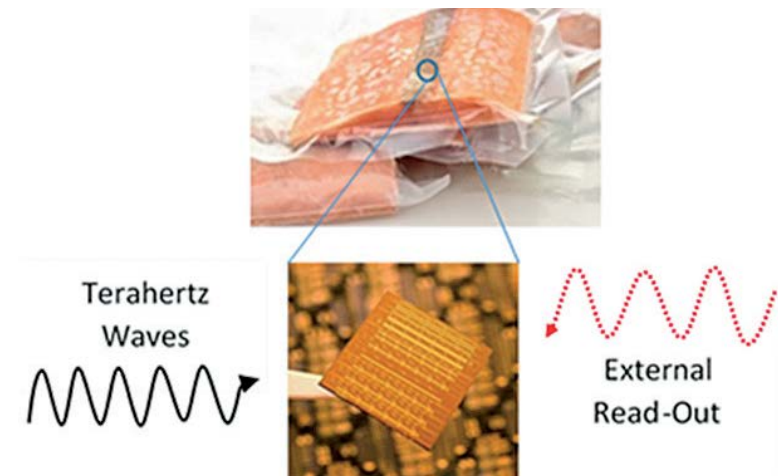
NON-DESTRUCTIVE TESTING

THz waves are very suitable for non-destructive testing in several industries:

- **Concrete inspection bridges and quays:** (defects, corrosion on reinforcing bars, water diffusion, cracks)
- Surface corrosion in shielded copper conductors
- Ceramic tile adhesion detection
- Mechanical deformation of polymers
- Insulation in buildings and space stations
- Building inspection

AGRICULTURE, NUTRITIOUS AND AFFORDABLE FOOD

The distinct absorption lines within different ranges of the THz spectrum of different pesticides and other organic materials make THz technology ideal to detect their presence. The fact that water is opaque to THz radiation also allows for detection of their hydration levels.



Terahertz technologies supporting sensing and imaging for agrifood.

The development and widespread deployment of sensor technology will allow individualised "sell-by" dates that replace the hypothetical risk of spoilage with the actual risk. A significant cause of food waste at the retail and consumer level could, therefore, be eliminated.

Photonic sensing has a crucial role to play in fish, shellfish and algae farming as the sector increasingly shifts towards more complex land-based, indoor systems. There is a growing need to minimise the destructive environmental footprint of traditional aquaculture. Smaller footprint and low-cost photonic sensors will be able to monitor water quality, oxygen and salt content, early development of pests and diseases, and the quality of the product itself. Even more challenging topics for agri-photonics are monitoring soil health, including compaction levels and the concentration of organic matter, nutrients and chemical residues. Terahertz technologies are specifically well suited to solve several of these challenges and therefore will be focus of my future research.

DETECTION OF FAKE DRUGS

According to the [World Health Organisation](#), tens of thousands of people in Africa die each year because of fake and counterfeit medication. The illegal counterfeit drug market is worth around €200 billion worldwide annually. The fake drugs are mainly made in China but also in India, Paraguay, Pakistan and the United Kingdom. Almost half the fake and low-quality medicines reported to the World Health Organization (WHO) between 2013 and 2017 were found to be in sub-Saharan Africa where substandard or fake anti-malarial drugs cause the deaths of between 64,000 and 158,000 people each year. THz sensors can measure whether active ingredients are present in samples.

TERAHERTZ WIRELESS COMMUNICATIONS - 6G AND BEYOND

Artificial intelligence assisted autonomous vehicles will become a reality, but it won't happen until 5G data networks are ubiquitous. The current 4G network is fast enough to share status updates or request rides, but it doesn't have the capability to give cars the human-like reflexes to prevent fatal car accidents. When it comes to autonomous vehicles, the speeds and data processing capabilities needed to mimic the timing of human reflexes are incredibly high. It has been estimated by people like Dr. Joy Laskar, co-founder and CTO of [Maja Systems](#), that the self-driving car will generate approximately two petabits of data per week—the equivalent of two-million gigabits.

ENHANCED 4G WILL NEVER BE FAST ENOUGH

To put this in perspective, even with an advanced 4G connection, it will take 200 days to transfer a week's-worth of data from a single self-driving car. That explains why we need much faster data processing technology and products.

Next generation chips and large 5G wireless connectivity will turn cars into "data-centres on wheels", thus enabling self-driving cars to make in-situ, complex, real-time decisions.

For a massive roll-out of autonomous cars that will be driven by artificial intelligence as well as being securely connected to the mobile network, not even 5G speeds will be enough - there will need to be lots of smaller mmWave and THz antennas located close to each other.

Terahertz wireless communications with terabit capacities go beyond supporting autonomous driving cars. It will transform the infrastructure needed to become a network of not only cars, drones, robots co-operating with each other but also interacting with (vulnerable) road users and even sensing the surroundings for environmental protection and safety.

The transition from research projects to missions serving society

In technology transfer, the “valley of death” is the metaphor often used to describe the gap between academic research-based innovations and their translation into commercial products for the benefit of society. Some other areas of the world talk about the “bridge to innovation” which is a kinder way of saying the same thing. Many companies cannot cross this “valley of death” without access to both public/private funding as well as access to relevant fundamental and applied research being conducted in Universities like ours. Raising funds for supporting research and creating state-of-the-art laboratories is a challenge for professors. I believe that Universities cannot effectively make an impact by just individual and isolated efforts.

FUNDAMENTAL CHANGES TO FUNDING AS FROM 2021

It is important to realise that the European Commission is changing its funding priorities for the period 2021-2027. Many aspects of the previous funding period, Horizon 2020, are being changed (e.g. references to the 6 Key enabling technologies have disappeared). Although the priorities will only emerge in detail towards the end of 2019, the new European Commissioner for Research, Science and Innovation appears to be following suggestions to adopt a funding policy more closely linked to the Grand Societal challenges. For Photonics, I believe this means the following contributions to solutions for:

- Instant diagnosis of major diseases
- Quality food from farm to fork
- Accident and congestion-free road transport
- A truly circular economy
- A million new jobs
- 10% higher productivity
- Zero downtime in a terabit economy
- Photonics as a flagship science for innovation

BEYOND THE TRIPLE HELIX



Societal challenges are very complex. To solve them requires going beyond the triple helix (co-operation between government, academia and industry). It also requires much stronger civic engagement. It means closer attention to the ways in which socio-economic issues interact with politics and technology, to the need for smart regulation, and to the critical feedback processes that take place across the entire innovation chain. Because forces that reject scientific explanations are becoming more influential, especially through social media. To quote from the excellent 2018 report by Dr Mariana Mazzucato.

Importantly, such challenges cannot be solved by any single European country, no matter how large it may be. Only at the level of the European Union, with its long experience of operating within a multilevel governance system, can we achieve the scale and diversity of talent and ideas to make real progress.

The sheer complexity and specialisation of science today means that attitudes of openness and collaboration are not merely a nice complement, but rather a critical factor for success. European Member States are at different levels of economic development, with some having invested much less than others in the key pillars of innovation: education and research.

Nevertheless, in every single country there are areas of excellence and expertise that could prove to be the critical factor to solve the challenges of today. The new Mission-Research approaches being developed for Horizon Europe are primarily a way to orchestrate the rich diversity of talent and expertise that today lies mostly fragmented or untapped across Europe.

To capitalise on this asset, Europe needs to take the next step and take advantage of its unique nature as a common market of diverse economies. **In addition to strengthening regional research and innovation capacities, Europe also needs European Union wide efforts to connect policies and grand challenges.**

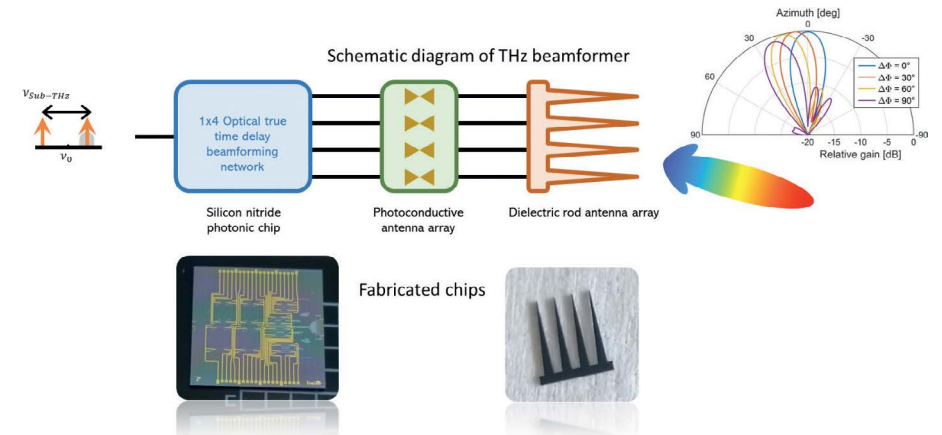
TERAHERTZ PHOTONICS: THE IMPORTANCE OF INTEGRATION

Now that certain sectors like integrated photonics and Terahertz technologies for sensing have reached a level of maturity, we're ready to start the connection process. Because unless some technologies integrate, they will never scale. **So, for example, secure connections are going to be needed between 5G networks and big data networks (e.g. connecting hospitals).** It is all about integrating these processes, so they can grow fast, efficiently and sustainably.

In information and communication, a new programmable optical infrastructure will be the 'central nervous system' upon which the digital society, industry and European economy will heavily rely. Photonics communication technologies are the optical lifelines of our modern society and economy, transporting data at an ultrafast pace in millions of extended fibre-optic networks around the globe in every home.

Highly integrated, accurate and fast photonic sensors with multi-sensor data fusion are the sense organs of the digital society. These light-based technologies, therefore, feed new Artificial Intelligence algorithms to enable autonomous driving, smart cities and Industry 4.0. They are essential to comprehensive understanding of climate change or breakthroughs in medicine and healthcare.

However, there are formidable research challenges ahead for the next decade for light technologies. This information and communication sector will need to deliver the required performance, resilience and cybersecurity, while satisfying cost, energy efficiency and technological constraints.



Example of Terahertz system for beamforming. Proposal for how it can be integrated into a single chip. Below progress of individual chips for building blocks of the systems. Next step is full realization in a single chip.

TERAHERTZ AND INDUSTRY 4.0

In the emerging industry 4.0 paradigm, advanced laser systems and the integrated use of sensor technologies for real-time parameter monitoring will be at the heart of completely digital and connected value chains. They are essential to allowing companies to move quickly between mass production of identical parts and the manufacture of individualised products.

TERAHERTZ AND HEALTH

There are significant challenges for Europeans working in life sciences and health. We are faced with an ageing society and the increase of age-related diseases as well as spiralling costs of the healthcare system. We are already seeing the development of mobile, wearable photonic devices. They will be combined with advanced biosensors for instant point-of-care diagnostics and treatment which regularly measure the wearer's medical condition and wellness. By doing this we can speed up early diagnosis and subsequent intervention, thus reducing healthcare costs and improving overall well-being. Affordable photonic-based real-time diagnostics to classify disease status, and to monitor and assess treatment responses, will open doors to the practical implementation of precision medicine.

All this leads to major improvements in the effectiveness of treatments. Future light-based developments may help to search for new biomarkers and develop promising treatments.

However, for all these solutions to become deployed at large scale, we will require full integration of designs in both electronics and photonics system. That means thinking at a system level.

Moving 5G Photonics from lab experiments to field trials

Now I would like to discuss the activities I am pursuing together with my team and colleagues and how they connect to my preferred vision of the future.

Research, development and deployment of communication networks will be key future economic differentiators. Without access to fast networks, European industry will not be able to be a global player. The need for smart network partnership development goes well in to the 2020's. The next Facebook, the next Google, the next Amazon, will be based on 5G technology.

Communication networks are the driving force behind many changes in our society. Photonics is starting to have a knock-on effect to different infrastructures like healthcare (needle-free testing for diseases), food safety tests for pathogens as well as environment monitoring on earth and from space. It's becoming clearer that light-based technologies on a chip are the key to building smaller, cheaper, faster devices to solve a lot of these challenges. Instead of just telling people about photonics technology, researchers will increasingly need to be part in field trials in non-photonics sectors (e.g. agri-food, medical, automotive).

The goal is to show these other sectors that 5G photonics and THz technologies are worth investing in and that it is win-win for everyone. Terahertz photonic chips, smart network and sensor services need to provide communication and intelligence where ever industry needs it - in a flexible way.

CREATING A TEST-BED FOR INTEGRATION AND TEST OF 5G USE CASES

Today our mobile phone infrastructure operates with the 4th Generation (4G) standard. Although the term 5G is currently being talked about by the publicity machines in the mobile phone industry, the final 5G specification was only decided upon in March 2019. So, although countries like South Korea and the USA claim to be rolling out 5G already, it is really an enhanced version of 4G. We only expect significant rollout of 5G in Western Europe around 2022, with many public

demonstrations during next year's European football championships. But a lot of technical challenges need to be solved before then.

The infrastructure needed to support 5G is going to be massive. It is beyond what most people can comprehend -and that includes industry specialists. Remember the telecom industry has taken the 4G capacity and transmission norms from 2010 and set themselves the goal to make the new 5G network 1000 times faster, reaching 7 billion people while using 90% less energy.

And the new factor is that 7 trillion Internet of Things devices need to be securely connected and operate with zero or extremely low latency. Yes, that is not a typo, I do mean 7 trillion because no-one wants to buy a device to find it doesn't connect reliably. And if the sensor is controlling the movement of a self-driving car or truck platoon, it must operate instantaneously. No connection is just not an option!

For many decades, our research teams in Eindhoven have been taking an active role in tackling those technical challenges. But now we're going beyond just being a lead partner in several international projects. **We're developing a test-bed to demonstrate that these technologies can work to solve many real-world challenges.**



European projects of the 5G PPP second phase. TU/e has major contributions to blueSPACE, 5G PHOS, MetroHaul.

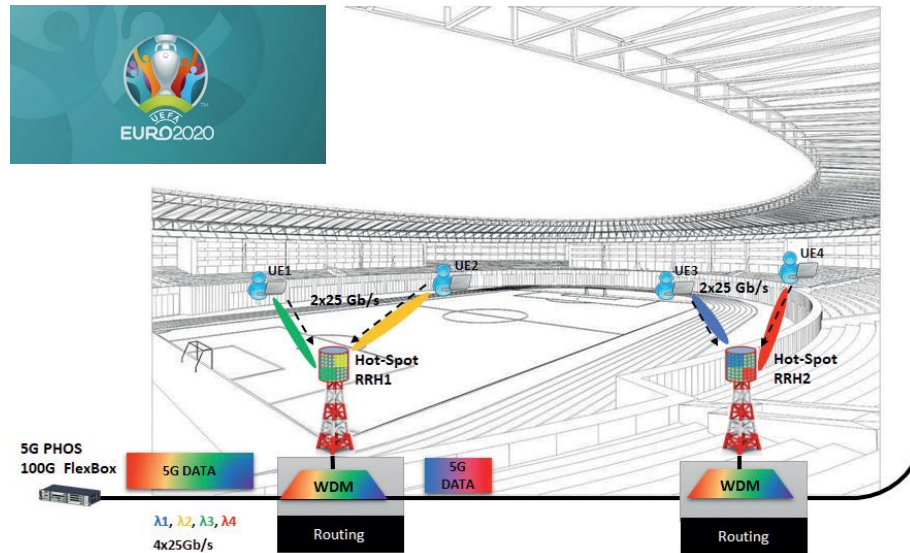
There are 21 European 5GPPP projects in what is called the second phase of the European 5G-Public Private Partnerships. I am coordinating the BlueSpace 5G-PPP which runs until May 2020. My team is also involved with other TU/e colleagues in 5G-PHOS, Metro-Haul, 5G MOBIX and CONCORDA, the latest from the third phase of 5G PPP and CAD EU schemes, respectively.

In practice this means that Eindhoven University of Technology is positioning itself as one of the global leaders in extremely low latency 5G link technologies.



My TU/e's team contribution to the BlueSpace PPP is our deep-domain knowledge of millimetre wave wireless technology as well as understanding multicore optical fibre infrastructure. 5G access points on the top of structures like lamp-posts will require "fibre to the antenna". The Eindhoven University campus is an ideal testing ground since it is already a "small city within a city".

5G SHOWCASE - FOOTBALL STADIUM



Final demonstrator of 5G PHOS for coverage in professional football stadium solving the challenges of highly dense hotspot requiring large peak capacity, low latency and flexibility.

High-profile trials, accessible to large public audiences are planned in two years. The target flagship event should serve as a milestone for industry, governments and the general public, showcasing the benefits for individuals and society. The UEFA EURO 2020 football championships will be played in 13 different European cities (Glasgow, Dublin, Copenhagen, Budapest, Bucharest, Brussels, Bilbao, Amsterdam, Saint Petersburg, Rome, Munich, Baku and London). This makes the EURO 2020 an excellent opportunity for a 5G Pan-European trial, also because of the media attention it will get. The timing of EURO 2020, in the summer 2020, is just prior to the 2020 Olympics in Japan.

SEVERAL 5G SERVICES THAT WILL BE TRIALLED

Three different types of trial services are proposed:

a. In the vicinity of stadiums and in fan zones, 5G Augmented and virtual reality applications related to EURO 2020 or football in general can provide ways to

entertain fans before, during and after the game, including through immersive experiences around the competition. These services are not confined to the hosting cities.

b. EURO 2020 will be the opportunity to demonstrate services in autonomous transportation around the stadiums and relevant transport routes. Scenarios include transportation to and from the airports and automated vehicles for the transport of officials, staff and supporters.

c. Public safety authorities dealing with security around the stadiums could benefit from Advanced public safety services. Augmented reality can be used to visually mark and track persons of interest based on facial recognition. Tailored services (e.g. access security, person localization) will create a significant higher level of both safety and security.

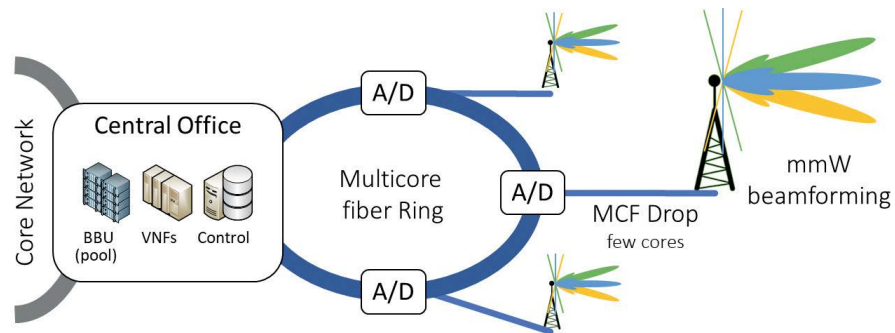
The final demonstration of the 5G PPP project 5G PHOS will take place in the professional football stadium of Thessaloniki in the beginning of 2020. It will showcase 5G mmw communications links to provide 3D experience and dedicated multigigabit access to spectators. Contributions on analogue "radio over-fibre" and optical beamforming and its integration over optical fibre communication infrastructure are being provided by my TU/e team members. Together these various TU/e projects will have considerable impact on the commercial deployment of these new services.

ROLLOUT OF FIBRE-TO-THE-ANTENNA

In order to develop a fast yet secure proposition for the mobile network operators, (and their customers), we are working on a different architecture approach for 5G. For instance, today many mobile base-stations use electronic switching inside the base-station mast and then convert this to an optical signal at the base where the fibre comes in. It turns out that this is one of the biggest bottlenecks in the existing 4G network. So, we're looking at bringing the fibre all the way up the mast and connecting it directly to the smart base-station antenna. To the reduce power consumption by the network, our teams at TU/e are involved in designing smart antennas that can beam a more concentrated signal in the direction of the mobile phone user.

We are working with a UK company called [Optoscribe](#) who are making the connections between standard single core optical fibres and our new multicore solutions which may have as many as 19 cores inside the same cable. These multicore cables carry many times more data bandwidth but require newly designed components to connect them - like fan-in, fan-out, splitters, and combiners. Our goal in Bluespace is to build multiple cores into one single fibre without enlarging the diameter of the cable.

Of course, we're not trying to do this alone. We're pleased that we're able to enter into a technology transfer agreement with [Corning](#) who have become a major partner within Bluespace. Most consumers know Corning as the developer of Gorilla Glass for mobile phones. But they are a major force in specialty glass and optical physics. We anticipate these multicore products will come onto the commercial market within the 3-year projected lifespan of the BlueSpace project. They will be used to directly feed optical signals to the antenna of a base station. In Eindhoven University of Technology, we will focus on providing fast low latency links and then develop the secure connections to support robotics, cooperative drones, automotive driving and LIDAR applications.



5G project blueSPACE multicore fibre ring and millimetre wave optical beamforming techniques low latency 5G communications.

To reduce the overall power consumption of the network, we're involved in designing smart antennas that can beam a more concentrated signal in the direction of the mobile phone user. Once a caller dials a number, the 5G mast will work out the location and beam direction from the incoming mobile signal and then optimize both the transmission and reception. This beam-forming is best done optically so it can cope with many simultaneous users accessing the base station from different directions. With an estimated 18 million masts needed for

a global 5G network, a lot is at stake if we want to reduce power consumption by 90%. In blueSPACE, the company LionIX International is providing the optical beamforming technology on-a-chip.

We're currently defining the verticals for the demonstration of the BlueSpace capabilities on the campus of Eindhoven University of Technology. Work on that starts soon - expect more details on the website to go live in late-2019. And the results are also going to be demonstrated in the laboratories of the largest Greek telecom operator [Cosmote](#).

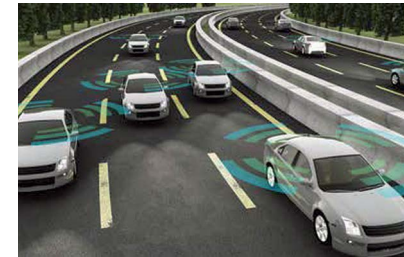
The connection with robotics, autonomous cars and quantum technologies

As well as mobile telecom, photonics and high capacity optical fibre infrastructure is crucial for other areas that demand reliable, instantaneous connectivity. Take smart factories, for instance. It is becoming important for robotic devices to collaborate in real-time with each other. Robots will also need to interact with human operators, video cameras and sensors. And the connection between these robots is going to be based on 5G photonics because only “instantaneous” technologies can provide the low latency requirement as well as robust, secure and reliable connectivity. In these situations, you cannot afford to have any down-time or intermittent connections. Many of these robots will need to access video or images that is stored in the cloud, i.e. on data servers that could be physically tens of kilometres away. 5G and THz photonics are key to addressing the issues of having enough bandwidth between the robot and the server in the cloud, as well as ensuring the very low latency. Once this is working, it is easy to extrapolate that scenario to autonomous and agricultural robots. This is also relevant for robots that need to cooperate for search and rescue in natural disaster recovery or dangerous demolition tasks.



We are currently investigating ways in which we can team up with other departments within Eindhoven University of Technology as well as external parties to solve some of the challenges ahead for the automotive industry. In autonomous driving you also need low latency with extremely robust, secure network connections to edge computers operating in the cloud. The scale of that network is very large.

At this year's CES consumer technology show in Las Vegas, the technical press noted that while the current LIDAR technologies work on the highway, the car navigation systems seem to get confused in urban settings with a lot of pedestrians, cyclists and tall buildings. Researchers in Northern Europe also point out that the trials in California don't have to contend with ice and mist. 5G-Photonics can also play a role here, because there's a similar need for instantaneous, high data-rate, secure, robust connections between cars and control centres.



AUTONOMOUS VEHICLES RELY ON ULTRA-FAST SECURE NETWORKS

In July 2018 we saw the first project announced in the final phase of 5G Public Private Partnership with the EU's Horizon 2020. Eindhoven University of Technology is involved in the first cross-border trials of self-driving vehicles in what's being called “autonomous driving corridors” -5G MOBIX. There will be a German-Dutch corridor alongside similar corridor trials to be held in South Korea and China.

This is very exciting for all the 5G technology drivers. Our contribution from Eindhoven is to integrate and validate 5G communications technologies for the “platooning” of cars and trucks. International standards need to be set soon so that cars can engage with other nearby vehicles and identify other road users.

As well as the need for instantaneous secure networks between cars, vehicles also need to communicate to devices by the side of the road. The added challenge is that licensing and traffic control is organized nationally in most countries. We need to see how these systems hand over when a vehicle crosses a country border. Although there may be similar systems on both sides of the border, they often have different operators. And because of differences in terrain, there may be variations

in the traffic rules (for example minimum distances between vehicles or maximum safe speed limits). There is a lot of work to do with certification, testing and engineering validation issues.

Another contribution from TU/e in 5G MOBIX is developing techniques to provide seamless hand-over among 5G networks and even operators. These scenarios will be tested in the campus test-bed being developed which I mentioned earlier. This is great news for several faculties at Eindhoven University of Technology as well as for the Automotive Campus which is just down the road in Helmond. We're all pulling together to make this a European success for the Brainport region.

We need to bring together expertise in secure wireless communication, in 5G Photonics, optical fibre links and localization algorithms. We also need mechanical engineers who understand precisely how drive chains, dynamical control systems, and cyber-physical control operate in modern cars, as well as those who understand how to build dynamic maps to plot the moving vehicles and physical changes to the roads. Autonomous cars will need to know exactly where active roadworks are taking place and that won't be plotted on standard navigation maps we use today. Again, that means we need engineers who can think at a system level! My team has joined the CONCORDA project and is already contributing with our expertise on 5G millimetre waves communications, measurements and test for extreme low latency performance.

PHYSICAL LAYER SECURITY AND QUANTUM CRYPTOGRAPHY

The security aspects of autonomous driving are complex. On the one hand you do not want hackers at the side of the road to gain access to the navigation system in the car. You may recall this has already been a major issue in the past. But at the same time, you don't want anyone to interfere with the access points at the side of the road. Remember that some edge computations will take place locally at the curb side, to improve the response times and lower the latency. The overall results of those computations are sent off to the data centre where they keep track of the overview.

In short, you need a very high level of data integrity and security to keep the system safe. Therefore, in my team we are working on techniques for providing data security at the physical layer for 5G wireless links. We are also, in cooperation

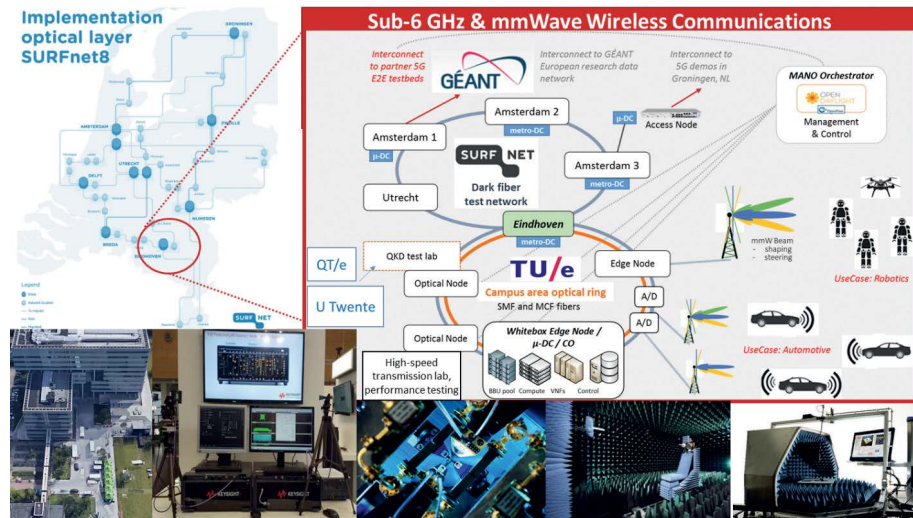
with colleagues from other groups at TU/e, on integrating quantum cryptography and quantum authentication into secure critical infrastructures such as for 5G.

THE ROLE OF PHOTONICS IN QUANTUM CRYPTOGRAPHY

We're going to be hearing much more about Quantum Key Distribution (QKD) as an essential cryptographic method. It is rooted in quantum mechanics and what has come to be known as quantum information theory. QKD has grown into a technology, that is ready to become a key system component for ultra-secure (= secret and authenticated) communication. It can be seamlessly integrated into existing telecommunication infrastructure, becoming a major building block of secure optical networks both optical fibres guided and free-space optical systems. Several business cases in datacentres, 5G, autonomous driving, and e-health require very secure data transmission as well as long-term storage. Very secure systems based on quantum cryptography rely on random number generators and quantum properties of light. To bring these applications to market needs the development of photonics technologies ranging from single-photon detectors and sources to amplifiers for quantum communication in mass deployable chips with corresponding trusted electronics and packaging.

TU/e teams at different faculties are working on making these breakthroughs. Now the next step is to bundle isolated efforts into a major mission-the creation of trusted critical infrastructures so important for the future of our digital economy.

Building Eindhoven's large photonics demonstrator



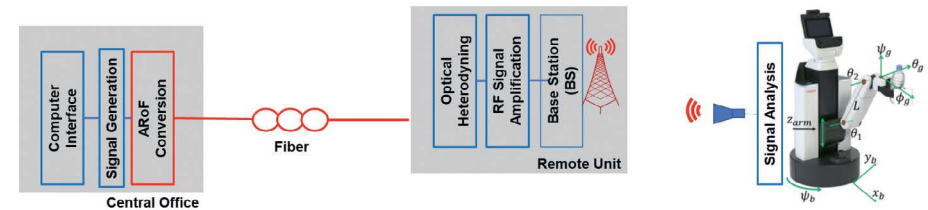
Eindhoven test-bed connecting device test, (sub)systems prototyping, new campus optical fibre ring, millimetre wave wireless infrastructure for 5G, quantum key distribution, edge computing and the validation of use cases such as automotive, cooperative, and security.

THE GENEVA COMPARISON

You may remember that 11 years ago, the European Laboratory for Particle Physics **CERN** in Switzerland started operation of the Large Hadron Collider. It's the world's largest and most powerful particle accelerator, built to test and demonstrate various theories in particle physics. The LHC consists of a 27-kilometre ring of superconducting magnets surrounding the city of Geneva, with many accelerating structures to boost the energy of the particles along the way.

In a similar vein, we need a testbed to demonstrate the capabilities of light-based technologies to both research institutions and large enterprises. Work has started to build an extremely fast optical-fibre ring built around the campus of the Eindhoven University of Technology. Our BlueSpace 5GPPP project has been

allocated four empty ducts in this ambitious project. Very soon we hope to be one of the first to deploy cables composed of next generation multicore optical fibres. Extensive 5G tests using spools of these fibre types and under controlled conditions have been successfully performed in our labs in the University's Flux building. Electronic components and sub-systems are tested at state-of-the-art wireless communications laboratories at the center for wireless technologies (CWT/e). But now we will be able to test their performance under real-world conditions and in real-time in a real-world use case.



Building a 5G test-bed for test and validation of low latency mmw 5G links for Robotics and other Industry 4.0 related use cases. Connecting labs and facilities for close to end-user test environments.

REACHING BEYOND THE CAMPUS THROUGH INTERNATIONAL COLLABORATION

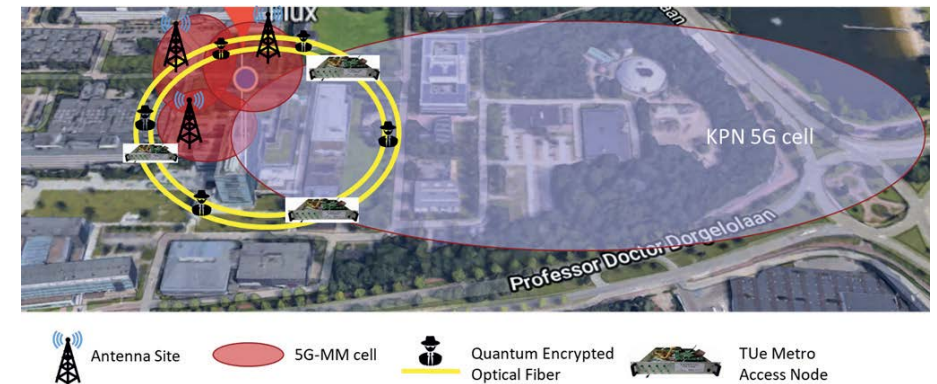
The campus of Eindhoven University of Technology is an ideal testing ground. The campus terrain in the city-centre is like many urban city situations - tall buildings, parks and narrow streets. We are setting up what we call the TU/e 5G testbed. It's going to be composed of the new optical fibre ring that will surround the University campus with tap-in and tap-out points in the lampposts and a number of key access points. Novel multicore optical fibre will be used to connect the laboratories in the Flux building with a 5G base station in the campus. We're aiming to build a network that will support 100GB and beyond capacity to the antenna. We will use multiple array antennas which should deliver a wireless speed of around 10 Gbit/s to mobile devices.

We will be able to connect to other nodes around Europe so that there will be ways for our partners to access the demonstrator remotely. This is done by support and cooperation with Surfnnet. So, let's say you are developing a new model for support in the backhaul/fronthaul - that can be tested here. Or you might be developing optical routing nodes and modules for the edge computing. That can also be tested here. And we envision connecting these 5G optical fibre base stations with an optical outer campus optical fibre ring. This will be about 40 kilometres of fibre around the city of Eindhoven and that we envisage this will become the basis for a quantum key-distribution testbed. Here we are cooperating with the local operator in the municipality of Waalre and the new "smart district" in Helmond.

We need to achieve instantaneous transport of data between those access points and to ensure that data centres are very secure. All this will be optical fibre based, because you need zero latency and very low losses across the large distances. Once the test systems have been thoroughly tested, then comes the challenge of massive deployment. A robust architecture is going to be needed most likely using cooperative approaches of satellite links, optical fibre links and free-space optical links.

THE ROLE OF PHOTONICS INTEGRATION TECHNOLOGY CENTER

Photonic integration technologies are going to be key in making systems with a small form factor, which are fast, secure and affordable. There are several projects going on in parallel to achieve this. For example, in a recent joint effort between our Photonic Integration Technology Centre and the Center for Quantum Materials and Technology Eindhoven we are building an environment for testing QKD as a service. In this way, the partners of the Photonic Integration Technology Centre will have access not only to the facilities for developing photonics chips but also for development and testing of systems involving **Quantum Key Distribution**. It will mean offering our partners access to an infrastructure which allows for "real-world testing" conditions and for developing new user cases. It is also our ambition to become an essential partner in the certification of such novel products.



Extension of TU/e 5G test-bed to include Quantum encryption for critical infrastructure such as for autonomous driving and hand-over 5G networks.

The urgent case for energy efficiency

ACHIEVING THE 90% REDUCTION IN POWER CONSUMPTION FOR 5G

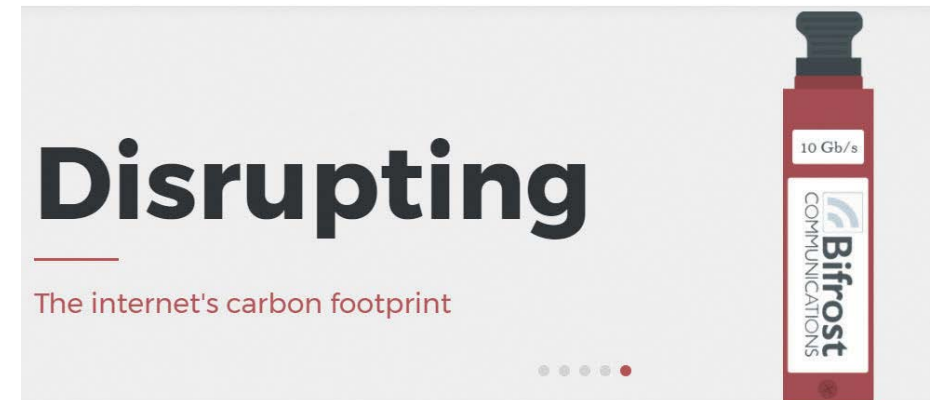
The tremendous popularity of mobile devices such as smart phones and tablets, as well as cloud-based services for business and personal use, means that around 70% of users in Europe now access the Internet via wireless connections. Globally, about 1.6 Exabytes of mobile data was being generated per month, according to Cisco's Visual Networking Index (VNI) report published back in 2014. All this is having a dramatic effect on mobile network power consumption. Today, operators are spending an estimated \$2 billion a year simply to power their networks, and base stations are consuming a high proportion of that budget. According to figures from Vodafone, base stations account for almost 60% of total mobile network power consumption, while 20% is consumed by mobile switching equipment and around 15% by the core infrastructure. A typical 3G base station uses about 500W of input power to produce only about 40W of output RF power.

The typical average annual energy consumption of a 3G base station is around 4.5MWh. So, it is no wonder that with an estimated 5 million base stations globally, researchers are looking at ways of reducing the energy bill as well as the large amount of carbon dioxide emissions and heat. In the 5G PPP BlueSPACE project we look at the use the combination of analogue radio over fibre and integrated optical beamforming technologies to reduce the complexity and power consumption at the 5G base stations.

A crucial role here is played by the current opportunities offered by photonic integration to transform efficient microwave photonics technologies into compact and energy efficient circuits that will play an important role in 5G. TU/e is a pioneer in this respect through the work of Joint European Platform for Photonic Integration of Components and Circuits which is based in the Flux Building at TU/e. JePIX has lead the way in dramatically reducing the cost of access to photonic integration design and fabrication by adopting the multi-project wafer approach.

However, to produce successfully mass deployable products, photonics components need to work in combination with electronics. This explains why there

are several projects in Eindhoven, like WIPE, currently investigating how to build hybrid electronic/photonics systems onto the same chip.



VALORISATION OF BREAKTHROUGH TECHNOLOGY: BIFROST COMMUNICATIONS

Let me explain more about that Danish start-up Bifrost Communication that I am involved with. It is a start-up from my former team at the Technical University of Denmark (DTU) who are working on a flexible channel selective receiver. They can pick out light signals that are 10 times weaker than conventional PiN photodetector-based receivers do today. For the first time, multiple channel fibre-based internet to the home or business is going to be possible up to 40 kilometres from the digital switch, instead of the current 10 km.

This translates into a reduction of millions of Euros in costs for both operational and capital expenditure for the providers.

At the same time, the technology makes it possible to configure 8 times more users (256 instead of 32) on the same fibre. We think all this means internet providers can decommission 90% of their central switching facilities. They can do this with low-cost standard lasers, and the system is fully compatible with the fibre that is already in the ground. The prospect of using the same technology for 5G signal transport to the antenna and to the central radio access (RAN) nodes bring advantages in energy consumption and re-use of optical fibre infrastructure and a smooth scalable solution to very dense 5G cell scenarios.

MASSIVE DEPLOYMENT OF INTERNET OF THINGS

At present, the Internet of Things benefits from photonics, and indeed it could be argued that in the future, without photonics the massive deployment of IoT would not be possible, considering that most of the communication will eventually be transported by photons, as part of a fibre-based core network. However, there are also photonics-based sensors such as cameras, infrared sensors, hyperspectral imagers that will also become IoT enabled.

In the future, more data will be generated and transferred as a result of more devices being connected. Requirements on data capacity, speed and security of data will increase, putting additional requests on an optical fibre communication system. This requires R&D efforts to produce energy efficient devices capable of arranging data so that only essential information is transferred and can easily interface with other devices. The expected high volume of sensors will drive the need for low-cost devices, which, in turn, will call for the development of new photonics sensors that are cheaper while maintaining the same performance and even energy self-harvesting.

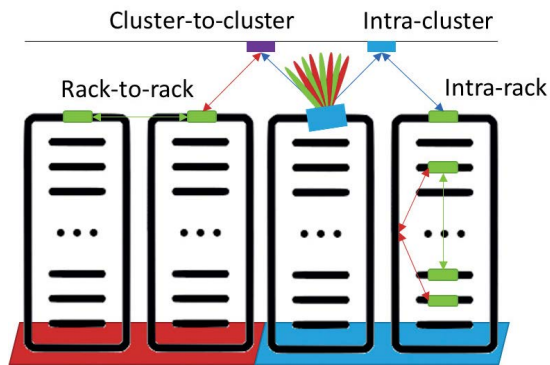
TERAHERTZ COMMUNICATION AND DATA CENTRES

Datacentres have a consolidate position in the interconnected world and in our digital economy. Datacentres will migrate from being today's content storage, cloud services and become essential for massive deployment of AI based services. Therefore, the growth of hyperscale datacentres is likely to continue. For the deployment of autonomous driving vehicles, a large amount of edge computing datacentres will be deployed. Common challenges for future datacentres include energy efficiency by scaling, security, management and control but also the maintenance and architecture of the connectivity inside the datacentre. The dominant connectivity solution in datacentres is to use wired connections by optical fibre links and/or copper backplane interconnects. This approach has two problems, cable complexity and hotspots. Hotspots, also known as hot servers, are servers that generate high traffic compared to others in the network and they might become bottlenecks of the system. Therefore, research groups, included mine, are proposing wireless communications into data centres. This approach can help to scale existing wired data centres, realize a pure wireless data centre or provide back-up and restoration connectivity paths

We are studying and developing technologies for THz terabit communications in Datacentres. The challenges that THz communication can help solving are the manual interventions to install and manage large cabling structures. Moreover, it can help to save space that can be used for providing other services. A promising feature of THz wireless communications is its combination with software defined networking for no-touch reconfigurable link establishment between nodes or racks.

Using dynamic beamforming and steering, Terahertz wireless links can be rearranged dynamically. This makes it possible to perform adaptive topology adjustment, establish back-up links in case of failures, and to provide capacity to a specific hotspot in the datacentre as traffic demands dictate. Such THz wireless data links can be implemented using dynamic beamforming and thus avoid using switches. My team is working on approaches to bring such functionalities such as "THz System on chip". Therefore, we will be working on system wide design and implementation of multiple emitters and receivers (MIMO), improving receiver sensitivity, moving towards higher frequencies, and exploiting the synergies and co-integration with photonic, electronics and signal processing.

Preparing TU/e students for future Careers



Terahertz wireless links with terabit capacity and dynamic beamforming and steering can solve the problem of hotspot servers in Datacenters, provide flexible topology re-arrangements, options for back-up and restoration connections.

If photonics is going to find and train the right talent of tomorrow, then it requires a new type of thinking when it comes to education. I would like to cite the example presented by my TU/e colleague Professor Maarten Steinbuch for StartupDelta. He described important trends in education in mechanical engineers:

".... I realized during lengthy discussions with industry, that the automotive industry was starting to move away from mechanical engineering. Today's cars are becoming a combination of computer science, electrical engineering and human-technology interaction, and just a 'bit' mechanical engineering. The automotive industry has been asking Universities to train more students because their business is growing. So, I asked them what type of engineers they needed. The answer was clear - we need more engineers who can think at the system level. For instance, if you want to improve a classical car to drive more efficiently, you need to understand combustion technology, but also aerodynamics, mechanics and electronics. For an electric car, you need an electrical engineer and a specialist in energy management. In other words, you need people who can think in a connected way."

".....System thinkers are always able to see the bigger picture, which is why they end up leading the larger and more complex projects in the company."

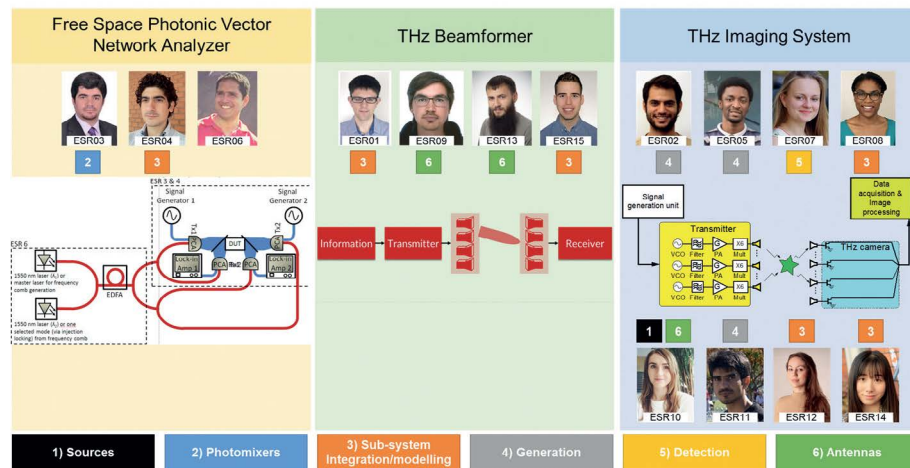


The same situation is true for photonics and terahertz technologies. We need to train students to be comfortable with integrating the vast knowledge we have of photonics, electronics, software, artificial intelligence, food, sensing and most importantly to understand how this fits into the global picture. We need to train researchers to think on the *system level* and able to actively interact with others if we are to solve large and complex societal challenges.

In the ITN project CELTA that I have the honour to coordinate, we have started to do this. Together with my colleagues, we are training 15 PhD students around converging Terahertz electronics and photonics for communications and sensing applications. We started by working on common engineering language of electronics and photonics at special workshops during our summer schools by focusing on a specific application case. Three teams are working on realizing each a final CELTA project demonstrator for beamforming in THz communication, a THz camera and a THz vector analyser, respectively. The CELTA project will be

concluded in February 2020 and the final demonstrator on THz beamforming is led and performed in TU/e. In another ITN project, 5G STEP FWD, together with colleagues from antenna design we co-supervise two PhD students on design and realization of mmw antennas integrated with photonics for compact remote antenna sites. And most recently we have received a grant to pursue further this research direction.

ITN CELTA Demonstrators



The ITN CELTA project is training 15 PhD students in the convergence of electronics and photonics. In multi-disciplinary teams they will demonstrate by the end of the project three prototypes of THz solutions for beamforming, vector network analyser, and imaging system.

Concluding remarks

In 2017 I returned to join the Eindhoven based [Institute for Photonic Integration](#) as full professor and to help establish the Photonics Integration Technology Centre. I say "returned" because I already know this region of the Netherlands as an incredibly collaborative and innovative hotspot.

COLLABORATION IS THE KEY TO INTERNATIONAL SUCCESS

Two years later, I am delighted with the results achieved so far. We have established an exceptional team at TU/e Eindhoven composed of very talented and ambitious PhD students, postdoc and project assistants coming from many different countries and academic backgrounds. Together, we are pro-actively teaming up with other groups across the departments at TU/e and with companies and initiatives in the Brainport region. Our teams have much to contribute to the development 5G photonics technologies as well as building a world class testbed for 5G and Quantum Secure demonstrators. More recently, we started efforts together with colleague professors in THz related topics and their teams a Terahertz focus laboratory.

The prospect of a photonic integration technology centre (PITC) acting as an essential bridge between fundamental research and product development will ensure rapid market uptake, from lab to fab. It requires an ongoing unifying effort from all stakeholder in the Dutch national photonic ecosystems and beyond. We are very honoured to be able to contribute and play an active role.

I believe it provides an excellent example of collaborative research and development fulfilling my preferred future for working across disciplines. By integrating knowledge and collaborating across departments we can solve critical societal challenges faster and more effectively.

I look forward to the next phase of collaboration with the world-class research teams at Eindhoven University of Technology as well as the brilliant companies around us. Together we can make an even stronger national and international impact!

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Curriculum Vitae

Prof.dr.ir. Idelfonso Tafur Monroy was appointed full-time professor of Photonic Terahertz Systems at the Department of Electrical Engineering at Eindhoven University of Technology (TU/e) on July 7, 2017.

I spent ten very happy years at the Electrical Engineering Department from 1996 -2006, completing my PhD. and working as an assistant professor. In the intervening period between then and now, I founded and led the metro-access and short-range communications group in the Department of Photonics Engineering at the Technical University of Denmark until June 2017. I retain my involvement in a spin-out company there called **Bifrost Communications** which I helped to found. It has the potential of doing for 5G and datacentre communications that Bluetooth did for consumer device communications.

Idelfonso Tafur Monroy started his academic career in the Kharkov Polytechnic Institute in Ukraine, and graduated from the Bonch-Bruевич Institute of Communications, St. Petersburg, Russia, in 1992, where he received a M.Sc. degree in multichannel telecommunications. In 1996 he received a Technology Licentiate degree in telecommunications theory from the Royal Institute of Technology, Stockholm, Sweden. The same year he joined the Electrical Engineering Department of the Eindhoven University of Technology, The Netherlands, where he earned a Ph.D. degree in 1999 and worked as an assistant professor until 2006.

He has since founded and led from 2007 the metro-access and short-range communications group of the Department of Photonics Engineering at the Technical University of Denmark where he was Professor until June 2017. He has also been a guest Professor at the Beijing University of Post and Telecommunications, University of California at Berkeley and ITMO University Fellowship Professor.

Idelfonso has participated in several European research framework projects in photonic technologies and their applications to communication systems. He currently coordinates the H2020 ITN CELTA and 5G PPP BLUESPACE projects and participate in several other European and national research projects. His research interests are in Terahertz photonics, secure communications and sensing systems, and co-integration of electronics-photonics. He is co-author of over 500 journal and conference papers, two patents, and has graduated 20 PhD students.

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The logo for TU/e, consisting of the letters 'TU/e' in a bold, sans-serif font. The 'e' is lowercase and has a diagonal slash through it.

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