Prof.ir. Ton Koonen
September 24, 2021

VALEDICTORY LECTURE

Light work(s)

EINDHOVEN UNIVERSITY OF TECHNOLOGY

DEPARTMENT OF ELECTRICAL ENGINEERING

VALEDICTORY LECTURE PROF.IR. TON KOONEN

Light work(s)

Presented on September 24, 2021
at Eindhoven University of Technology

Introduction

Mijnheer de Rector Magnificus, leden van het College van Bestuur van de Technische Universiteit Eindhoven, beste collega's, familie en vrienden, beste toehoorders,

At the end of my formal appointment of more than 20 years as a full-time professor at TU Eindhoven, I would like to take you on a sight-seeing journey through what happened over all these years and how happy I have been to contribute my piece parts. Before TU/e, I was in industry for another 20 years, the last nine years of which I was already partly involved in academia as a part-time professor at the University of Twente. All these years have been dynamic and it has been a great pleasure to be involved in the incredibly fast-evolving world of optical communication from its early years onward. When you enjoy your work, it does not feel heavy, it feels 'light'… Hence the title of my valedictory lecture, '*Light work(s)*', where 'light' has a dual meaning: 'light' as an adjective to indicate that the work in this domain has been a real pleasure and 'light' as a noun to describe how light really is a very important vehicle which has enormous power to carry information and thus keep our society together…

Communication by means of light has been my 'Leitmotiv' all these years. It has been my drive for even more than 42 years. My 1979 master's graduation project at TU/e was about optical fiber communication, specifically the quality of digital communication which could, according to theory, be reached with the very early techniques available at that time.

After graduating from TU/e, I moved to industry, into applied research in the novel field of optical fiber communication. I accepted a job at Philips' Telecommunicatie Industrie in Huizen. Those were the days when Philips was still a truly diversified industry with a plethora of different products, including public telecommunication systems. Philips' Telecommunicatie Industrie was headquartered in Hilversum and, in some sense, was behaving quite independently from the giant in Eindhoven. My first job there was in applied research on optical fiber transmission systems. I joined a group that was just moving from Geldrop to Huizen. The group had completed a field trial of a fiber transmission system from Eindhoven to Helmond in 1978, bridging no less than 8.7 km with a data rate of 140 Mbit/s. This was the very first optical fiber transmission link in the Netherlands and it immediately set a new transmission record. This meant a significant step forward with respect to the actual coaxial cable systems, which could only bridge 2 km at that speed. But when it started in the early '80s, fiber was initially meant mainly to replace coaxial copper lines for long-distance transmission at 140 and 565 Mbit/s, so far less than what is possible today.

In my valedictory lecture, I would like to introduce you to the wonderful world of optical communication. My inaugural lecture at the University of Twente, held on 14 Oct. 1993, was entitled 'Netwerken in een ander licht' and sketched some outlooks [1]. In this valedictory lecture, I plan to highlight, in particular, how optical communication evolved from a technology which connects big entities like cities and industrial parks to a technology which is reaching out to individual users, to their homes and offices, and even inside these buildings in order to extend the information highway all the way up to your devices.

Fiber-to-the-Home has been installed in many cities and ever more homes are being connected. As a next step, fiber will also enter the home, preferably in combination with technologies for connecting your devices wirelessly. I will sketch some of the research we did on such advanced optical communication systems and focus on those which bring broadband connections down to users: spatially multiplexed systems, optical packet routing networks, flexible Fiber-to-the-Home systems, radio-over-fiber systems enriched with beam steering of the radio beams and optical wireless communication technologies which can provide the ultimate end-to-end all-optical connectivity.

Optical fiber communication

Over the last five decades, a very fast evolution of optical fiber networks has taken place. Whereas fiber links originally started as a powerful alternative to copper-based long-distance links between cities, they have expanded their territory a lot: at one end spanning across the whole globe and at the other end penetrating end-user's homes. There are many fiber-optic cables crossing the oceans, such as those bridging the Atlantic Ocean from Western Europe to the US east coast over some 6000 km and those across the Pacific Ocean from the US west coast to Japan via Hawaii over some 9000 km [2].

The optical fiber was invented in 1966 by Charles Kao together with George Hockham at STL laboratories in the UK. I once met Charles Kao at a conference banquet in Hong Kong; it was truly unique to meet the founder of fiber optics in person. Kao received a Nobel Prize only in 2009, unfortunately a bit too late as he was not in a good mental health anymore. At Corning, USA, Donald Keck, Peter Schultz, and Robert Maurer produced the first optical fiber in 1970, but it still had large losses of about 20 dB/km. Since then, enormous progress has been made in the purification of fiber glasses and in the control of production processes. Nowadays, fiber losses are as low as 0.17 dB/km, allowing a reach of more than 100 km. With its tiny single-mode core diameter of only about 9 mm, the transmission capacity of a single fiber has grown immensely to beyond 1 Tbit/s per wavelength, with room for over 100 wavelengths in the 1.5 mm wavelength bands where fiber losses are lowest. Single-mode optical fiber has much lower losses than coaxial copper cables and also much higher bandwidth, so no wonder that they have taken over in long-haul transmission links.

But maybe the most impactful difference which optical fiber brings with respect to copper cables is that fiber offers an extra dimension for the transmission of signals, namely the wavelength dimension. In a fiber, photons carry the information. These light particles have a wide range of colors and each color can be a separate transport channel within the same fiber. The fiber thus actually becomes a multi-lane highway in which each lane offers tremendous capacity and is independent of the other lanes. In copper cables, electrons carry the information and do not come in different colors.

Fig. 1 gives an impression of an optical fiber with protective coatings. Note that the fiber itself has a diameter of only 125 mm, which is about the thickness of a human hair. Its low-loss characteristics show an exploitable spectral bandwidth of over 50 THz, which enables it to carry, for instance, 1000 signal channels which each have a bandwidth of up to 50 GHz (!).

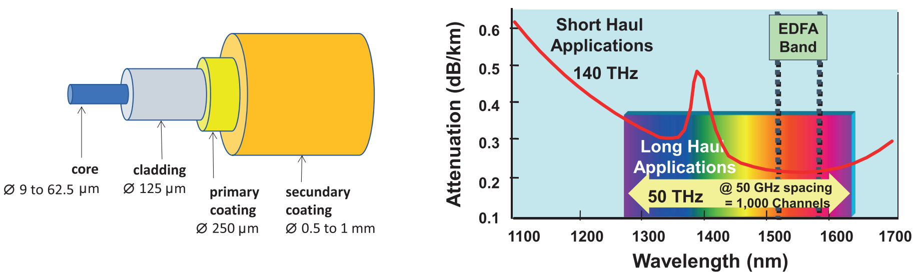


Fig. 1. Optical fiber and the loss characteristics of single-mode fiber.

Besides ultra-low-loss high bandwidth optical fibers, optical amplifiers are also needed to restore signals during long links. The erbium-doped fiber amplifier was another key invention, created by the University of Southampton (Dave Payne et al) and Bell Laboratories (Emmanuel Desurvire et al) in 1986-87. It is able to amplify channels in a wide range of optical wavelengths simultaneously (1525-1610 nm, i.e., C- and L-bands), no matter what their data speed is, and hence is an ideal device for intermediate all-optical amplification in transoceanic and long terrestrial links. It can thus optically amplify the full multi-lane highway in a single device.

Optical fiber communication networks

Communication networks are obviously not only about transporting signals from A to B but also need to bring signals to many different places according to the required destination.

So, the signals need to be routed in the nodes of the network. And again, the extra dimension of wavelength makes optical routers much more powerful than electrical ones. In particular, we have done a lot of investigations into all-optical routers. By using tunable wavelength conversion techniques, the incoming signals can be internally converted to other wavelengths and passive wavelength-routing devices then bring the signals to the desired output ports. The signals thus stay within the optical domain and are not first converted to electrical signals, switched and then converted back into optical ones; this would happen in electrical routing nodes. It may be compared to driving with your car to a roundabout and choosing the right exit: of course, you prefer to stay in your car and do not want to get out, walk to that exit and get into another car. All-optical routing nodes and add/drop nodes (e.g., [3]) hold great promise for high-capacity traffic streams; the routing itself is done all-optically and therefore does not limit the data communication speed.

Fig. 2 gives an impression of the layering of communication networks. The upper layer is about long-distance links (transoceanic, transcontinental and transnational). In the past, those links were made by satellite (with huge delays) and coaxial cables. Optical fibers have fully taken over here, with maybe some exceptions in almost deserted areas where satellites have to provide communication coverage. Within countries, fibers are connecting cities and city areas. There, routing nodes are needed to direct the communication to the various cities. Among these nodes are also the big data centers which are handling the booming internet traffic. And next come the access networks, where the connections to the homes, apartment buildings, offices and other buildings are made. These were originally done with twisted copper pairs or coaxial cables but have largely been replaced or are soon to be replaced by fiber; these links are known as Fiber-to-the-Home, Fiber-to-the-Building, etc. In the Netherlands, many homes are fiber-connected already. KPN, Open Dutch Fiber (with T-Mobile) and Delta are intensifying their efforts;

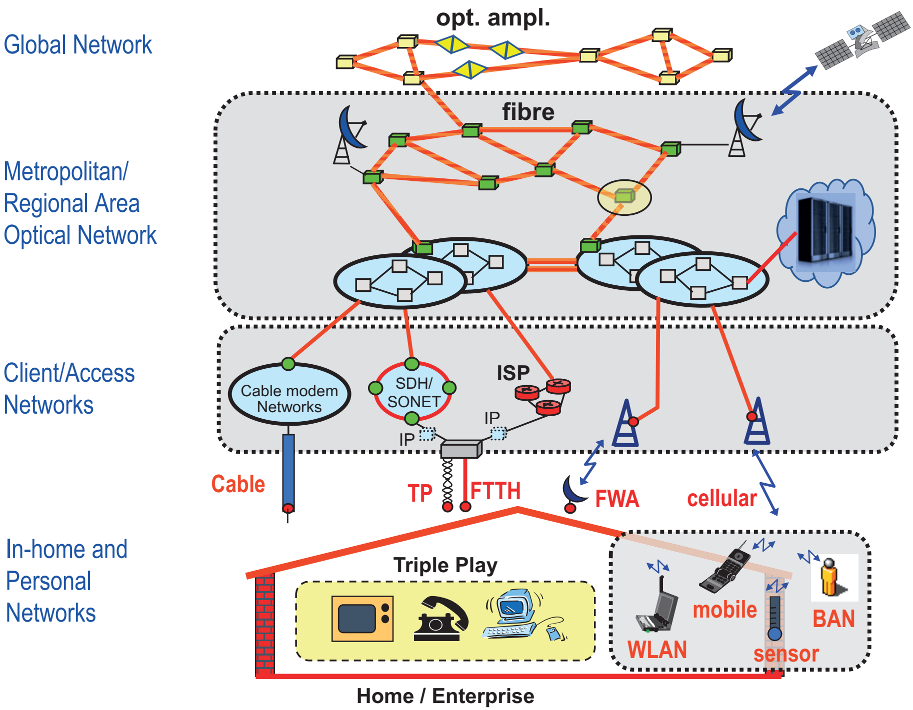


Fig. 2. Optical fiber networks – the fabric of our information society.

it is expected that all homes in the Netherlands will be connected by fiber well before 2030. Data speeds are then expected to be at least 1 Gbit/s per home.

Obviously, fiber to the doorstep of the user's home is not enough; the information highway should be extended into the home. This involves the last network layer: the in-home networks. Typically, triple play services are needed: voice, video and computer data. There will be a wide variety of devices for this, each with their specific needs: video screens, laptop computers, tablets, smartphones, local data storage units, etc. But in the upcoming Internet-of-Things age, there will also be many items asking for less bandwidth, such as household appliances like smart vacuum cleaners, washing machines and refrigerators, sensors for detecting fires and climate control, burglar alarms, body sensors, etc. The user typically wants all these in-home items to mostly be connected wirelessly, avoiding the restrictions of being bound to a wire. Typically, such wireless connections are made by radio technologies, notably Wi-Fi and Bluetooth. But these technologies have limited reach and need to be fed by a wired network for which fiber is the preferable future-proof unifying medium. A lot of research in our group is therefore being done on in-building optical fiber networks, through which we study how to transport and steer radio signals over fiber. Ultimately, our vision is for the entire communication connection to be optical, starting and ending at the user, and including the wireless part; this involves optical wireless communication, as we will see in the last part of this lecture.

Growing the capacity of fiber links

Driven by the fast-increasing use of the internet, both in terms of number of users and of bandwidth per user, the traffic to be transported by fiber is growing exponentially. Fiber techniques have made great advances in order to keep up with this growth, as shown in Fig. 3.

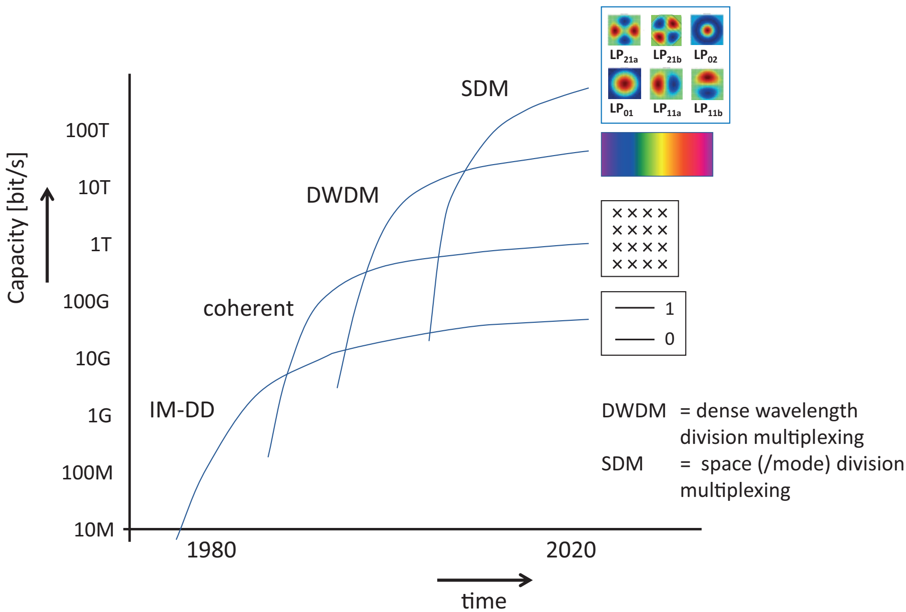


Fig. 3. Evolution of optical transmission techniques.

Starting in the '80s, so-called intensity modulation direct detection fiber systems used binary pulses of light which were only modulated by intensity, so 'on' or 'off'. This IM/DD technique needs a lot of bandwidth and does not use the fiber's capacity very efficiently. With optical coherent detection, it became possible to use more comprehensive modulation formats with each transmitted symbol containing more information, which implied a great step towards higher capacity. Next, multiple wavelength channels were introduced and such coherent communication is done in each of them. Through this so-called dense wavelength division multiplexing, the total capacity of today's systems can exceed 10 Tbit/s while using over 100 wavelengths. With multiple fibers inside a cable (a transoceanic cable [4] may contain eight fiber pairs or more, for instance), the cable capacity can be a large multiple of this. But even with this, fiber cable capacity has problems in keeping up with the exponentially growing internet traffic. So, as a last resort, the spatial dimension is being opened: whereas a single-mode fiber deploys only a single optical mode and thus achieves a huge bandwidth, there is also the option to use multiple propagation modes of the light in the fiber's core and to multiplex them in order to attain an even higher capacity in a single fiber core.

In the early days of fiber optic communication, fibers with a larger core (typically with 50 mm diameter) were used in which many light rays can be guided in parallel. Such multi-mode fibers are easier to connect and hence easier to install, but they had less bandwidth than single-mode ones due to the propagation time differences between these modes. But in our laboratories, we recognized that we could also split this large number of guided modes into subgroups and thus make each subgroup its own channel. Each subgroup then has less modes and thus a higher bandwidth. We called this 'mode group division multiplexing' and introduced it in 2002 [5]. With this technique, we created two advantages: multiple groups yield a multiple of their capacity and each group already has a larger capacity due to the reduced number of modes in it. To demonstrate the feasibility, our PhD students built a system which featured three mode channels, each at 10 Gbit/s over 20 meters of large-core multimode fiber [6].

In the meantime, other laboratories (particularly in Peter Winzer's group at Lucent Technologies-Bell Laboratories) came up with a similar idea for single-mode fibers [7]. By operating such fibers below their so-called cut-off wavelength, they are no longer single-moded but also guide higher-order modes in the same core. This enables so-called 'spatial division multiplexing' (SDM), thus creating a multiple of the huge capacity of a single mode. By now, this has brought fiber capacity to the level of Pbit/s.[1] Together with other European partners, we also worked on high-capacity SDM systems in the European Commission-funded MODE-GAP project from 2010 to 2015. In our laboratory, we built a system which deploys three modes in a single core using a fiber with seven cores and which achieved a total capacity of 255 Tbit/s in this fiber with 50 wavelengths and advanced high-speed signal modulation [8]. To get some feeling for this: a single telephone call without compression uses 64 kbit/s, so more than 3.5 billion phone calls can be transported together in this fiber of only 192 mm diameter, thus enabling half of

[1] 1 Pbit/s = 1000 Tbit/s = 1000000 Gbit/s

the world's population to talk to the other half. The entire world's population can therefore be connected through only a single tiny fiber!

We are continuing research in this track in our group, where my colleague Chigo Okonkwo (who took over from Huug de Waardt) and his co-workers are exploring novel multi-dimensional signal modulation formats and ways to increase the accessible number of modes in the fiber core. We are fruitfully working together with the Bell Laboratories group led by Peter Winzer in New Jersey – several of our PhD students worked with his team – and an order of magnitude increase in transport capacity has again come into reach, achieving Pbit/s speeds.

Optical traffic routing

The traffic in telecommunication networks has predominantly become internet-traffic, so traffic streams are therefore constituted by packets of data. These packets need to each be routed to their specific destination. Within the network nodes, very fast switching is needed to bring subsequent packets to the right addresses. The packet contains a label which indicates what its next address should be. The packet switching is controlled by the routing table, which reads the packet's label and determines which new label should be attached to the packet in order to get it to the right next node. This so-called label swapping should be done without changing the data contents of the packet.

In our group, we have investigated a range of optical technologies for this label-controlled packet routing while keeping the data in the optical domain in order to avoid limiting the node's throughput capacity. In the European Commission-funded project STOLAS (Switching Technologies for Optically-LAbeled Signals), which I was happy to lead, we have adopted the general architecture shown in Fig. 4 in which tunable wavelength converters change the wavelength of each packet [9]. More specifically, the data is carried in the packet through intensity modulation of the light, whereas the label of the packet is frequency (or phase) modulated. These modulation techniques are independent of each other, i.e.,

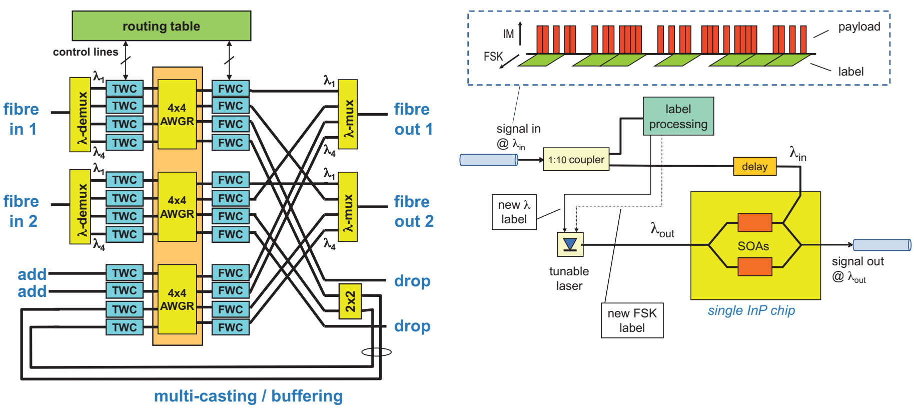


Fig. 4. Label-controlled packet routing node (left) with orthogonal label swapping circuit (right).

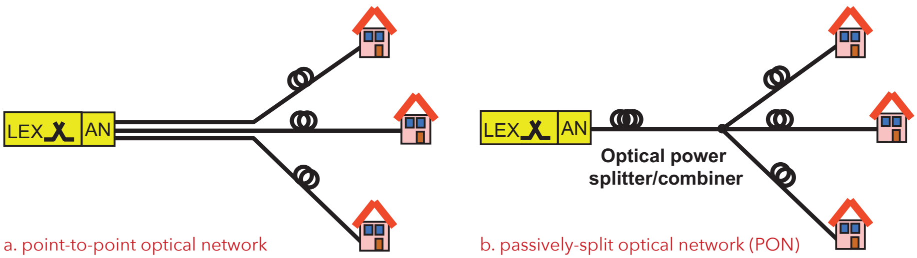
'orthogonal'. We can transfer the data to another wavelength by means of a wavelength converter circuit which maintains the intensity modulation, as shown in Fig. 4. And we can swap the label by modulating the frequency of the tunable laser diode which is pumping the wavelength converter. With this advanced technique, we can route the packet's data transparently through the network node and can also keep the label closely connected to the packet with the orthogonal scheme. This saves a lot of bookkeeping and signal processing which is otherwise needed to keep the data and label information of the packet together.

Besides routing packets in the network nodes, optical packet switching has become highly important in internet data centers which have to route massive amounts of packetized information among the huge number of servers inside the center. The networks inside a data center are also largely based on fiber, and optical routing between the servers without needing to do optical-to-electrical signal conversion and vice-versa can save a lot of energy and reduce internal delays. Data centers are consuming lots of energy and, with the booming growth of internet traffic, they have ever more work to do. So, saving energy and increasing speed through optical routing and signal processing techniques is highly relevant. Within our group, this area of research was initiated by Prof. Harm Dorren. Harm very sadly passed away in 2015 and we owe a lot to him. My colleagues Oded, Nicola and Patty are continuing the good work in this research domain, with great results in several European Commission-funded projects too.

Optical access networks

Fiber-to-the-Home (FttH) makes it possible to extend the optical superhighway all the way down to the user's home so that the last connection to the home is no longer the bottleneck in getting broadband services to the user [10]. Twisted pair copper cables were originally installed for telephony and have served as the final link to the user for decades, but these are inherently narrowband and need advanced signal processing to achieve higher data speeds. With so-called ADSL and VDSL, a few tens of Mbit/s can be achieved, but only over short distances of a few kilometers. Coaxial copper cables were originally installed for CATV and have a pretty large bandwidth of about 1 GHz. But again, they have a limited reach and need intermediate amplifiers in street cabinets to reach out to users' homes. Data transport at higher speeds can be achieved, up to some hundreds of Mbit/s. Both twisted pair copper cable access networks and coaxial copper cable access networks need to be upgraded each time when users require higher capacity and it is apparent that such networks are not future-proof as internet usage is increasing fast. The upper parts of these networks have already largely been replaced by optical fiber. But the installation efforts are the highest in the last cable meters to the homes, so network providers are hesitant to replace these last meters by fiber. For twisted copper pair cables, the urgency is the highest, so KPN, Open Dutch Fiber (with T-Mobile) and (more recently) Delta have already spent much effort on installing fiber all the way to the home. They have ambitious plans to connect every home in the Netherlands before the end of this decade. But Ziggo, with its broadband coaxial cable plant, is still less inclined to speed up Fiber-to-the-Home.

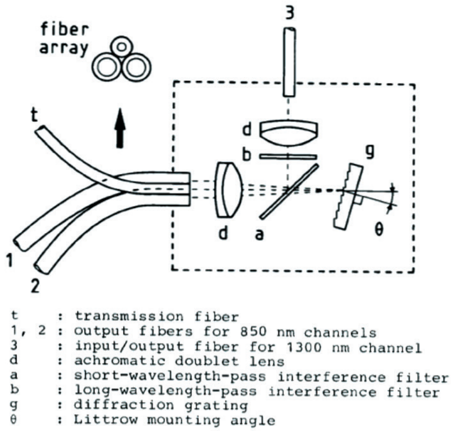
With FttH, connection speeds of up to 1 Gbit/s are typically offered, which is satisfactory for many residential services. For example, downloading the Lord of the Rings trilogy of 61 gigabytes would require 5.4 hours with a 25 Mbit/s DSL line, whereas this can be done in 8.1 minutes with a 1 Gbit/s fiber line. An FttH network may be installed in different topologies, of which the most relevant are point-to-point (P2P) topology and fiber-split passive optical network (PON) topology; see Fig. 5. When starting FttH installations in the Netherlands, point-to-point topology was mostly used; an example is the OnsNet FttH network in Nuenen, one of the first in the Netherlands when it was installed in 2005. It is easy to upgrade as bringing the user connection to a higher speed requires only the replacement of the relatively simple optical transceiver units at both ends of the fiber. But it also requires a lot of individual fibers to be installed as each house needs its own fiber. Installation costs are therefore relatively high. The PON topology uses a single fiber which is split into individual fibers close to every home. It therefore requires less fiber to be installed, but also requires an extra effort to combine the traffic from the homes together into the single fiber. By balancing installation costs versus equipment costs, preference may be given to either P2P or PON topology. It can be reasoned that PON topology may be more beneficial cost-wise for larger distances from the home to the local exchange and/or for higher home densities. For example, Delta has apparently recently chosen PON topology in its FttH plans for the province of Zeeland.



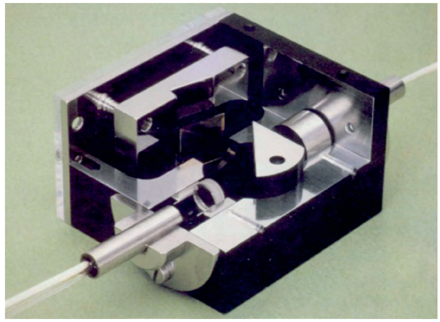
a. point-to-point optical network b. passively-split optical network (PON)

Fig. 5. Fiber-to-the-Home network topologies (LEX = local exchange; AN = access node).

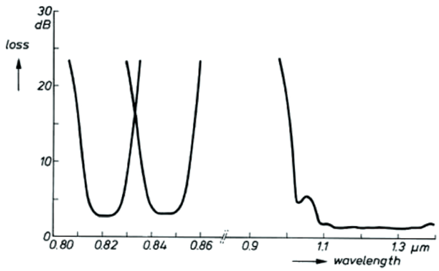
My activities in FttH date back to my first job in Philips' Telecommunicatie Industrie. In those early '80s days, graded-index fiber was used for long links with speeds of 140 Mbit/s and the Eindhoven-Helmond field-trial link of 9 km was the first in the Netherlands. But in these early days, people were already thinking of getting the fiber all the way to the user's home. My task was to enable the use of multiple wavelengths on the same fiber in order to have multiple services independent of each other. Fig. 6 shows the wavelength demultiplexer I designed, which could separate two closely spaced wavelengths in the 850 nm wavelength window for downstream traffic and add a wavelength in the 1.3 μm window for the upstream traffic [11] [12]. Bulky components were used in those days as integrated photonic circuits did not exist yet, so we used lenses, a reflective diffraction grating and interference filters. Fig. 6 shows the interior and the characteristics. A three-wavelength multiplexer was also built with a similar structure [13]. In total, we built 200 demultiplexers and multiplexers, which were put into a field experiment in the BIGFON – Breitbandiges Integriertes Glasfaser-Fernmelde OrtsNetz in Germany and worked very well [14]. I presented this in my very first conference paper at the European Conference on Optical Communication (ECOC) in 1981 [11], no less than 40 years ago.



a. demultiplexer configuration



b. demultiplexer module for field trial



c. wavelength characteristics

Fig. 6. Early three-wavelength demultiplexer for FttH (presented at ECOC 1981 [11]).

Since then, many evolutions have taken place in fiber access networks. Besides point-to-point FttH networks, a range of PONs have been introduced and standardized in ITU[2] with ever higher line rates. At present, G-PON (Gigabit/s PON) and XG-PON (10 Gigabit/s PON) are being installed, in which high-speed time-multiplexing is used to combine in the order of 64 users on the single feeder fiber. Wavelength multiplexing has also been getting attention in recent years in order to extend to 40 Gbit/s and beyond (note that we already looked into WDM in FttH in the '80s…).

In my industrial position in applied research, we recognized that the wavelength dimension can also be used for routing users' data streams in addition to its use for multiplexing towards higher data rates. By deploying transceivers with multiple wavelengths at the local exchange and wavelength routers in the splitting nodes of the PON, one can route each wavelength to a set of homes. The set can be

[2] International Telecommunication Union (ITU) is the United Nations specialized agency for information and communication technologies

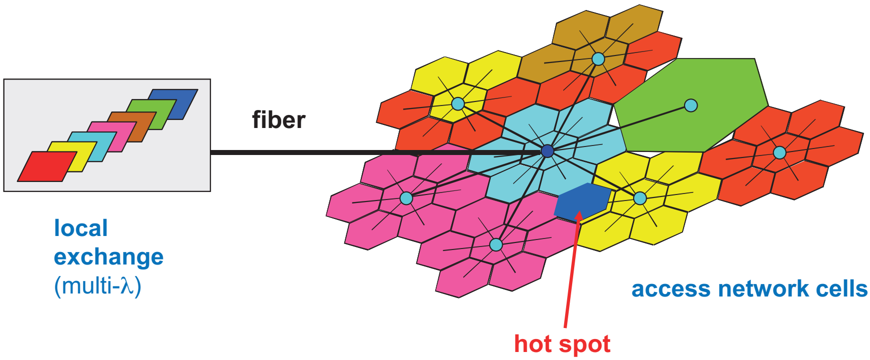
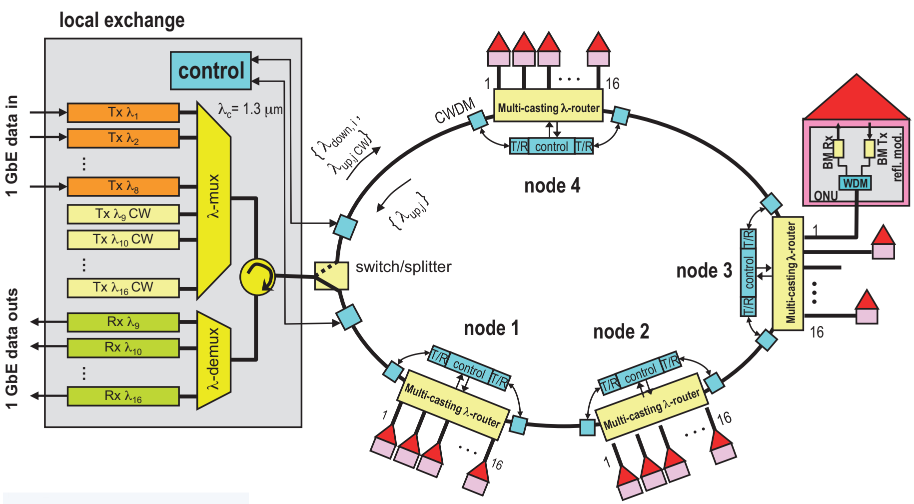


Fig. 7. Dynamic wavelength-routed FttH network.

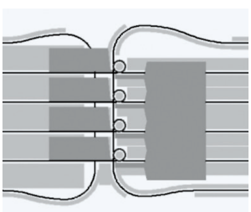
changed by setting the switches in the wavelength routers, as illustrated in Fig. 7. Homes which get the same wavelength have to share its capacity, so one can change the capacity available for a home when changing the wavelength routing and thus tune the home's capacity to its actual needs. It has been shown that this concept can significantly improve the efficiency of the whole network and provide capacity on demand to every home. We proposed this concept [15] and elaborated it with other European partners in a range of projects funded by the European Commission which I have initiated and led: the ACTS TOBASCO project (1995-98) on fiber-coax networks [16], the ACTS PRISMA project (1998-2000) on fiber-wireless networks [17][18] and the IST HARMONICS project (2000-2002, taken over by a colleague at Lucent Technologies when I left to TU/e) on packet-based hybrid access networks [19]. In various field trials, we proved that this flexible capacity allocation idea can indeed significantly enhance the throughput of a fiber access network.

After moving to TU/e, I also proposed this flexible PON concept in the Broadband Photonics project, part of the Dutch-funded Freeband program. In this project, later coordinated by my colleague Huug de Waardt, we worked together closely with Genexis, a FttH company established in Eindhoven by Gerlas van den Hoven. As sketched in Fig. 8, the local exchange contains multiple transceivers operating at different wavelengths. The homes are connected to the local exchange by a ring-shaped fiber network along which wavelength add/drop nodes are positioned to decide which wavelength or wavelengths are connected to each house.
The control of these add/drop nodes is done from the local exchange, so the network operator can remotely decide how much capacity each home will get in

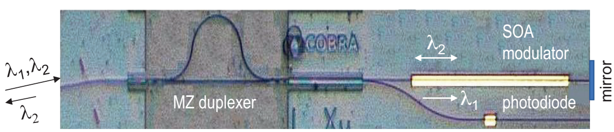
accordance with the general concept of flexible network coloring outlined in Fig. 7. Because of the ring topology, additional reliability is added to the network as an adjustable switch/splitter enables the data to reach the homes in a clockwise and counterclockwise direction and can thus circumvent a fiber break in the ring. The tunable wavelength add/drop nodes were made in a silicon-nitride (SiN) photonic integrated optical circuit (PIC) by Lionix and the reflective transceivers in the users' homes were made in an indium-phosphide (InP) PIC in our TU/e cleanroom. The system integration and validation was done in our laboratory, showing a high, flexible data rate access of 1.25 Gbit/s per home [20]. We showed analytically that the system can handle significantly more traffic load with this flexible wavelength allocation to homes than without it.[3]



a. Ring-shaped flexible fiber access network



b. 1×4 multi-λ add/drop PIC (in SiN)



c. Integrated reflective transceiver PIC (in InP)

Fig. 8. Wavelength-agile FttH network including protection

[3] With eight wavelength channels each operating at Gigabit Ethernet speed (1.25 Gbit/s) and 256 homes each asking for Poisson-distributed 125 Mbit/s connections, the system load can be 3.2× higher for an accepted blocking probability of 10^{-3}.

Wired optical indoor networks

Although the information highway can be extended to each home with FttH, there is still a last bridge to cross in order to reach users: the indoor network. As of today, there may be a variety of cable networks in each home, each tailored to particular kinds of services: twisted copper pairs for fixed telephone and fax (although mostly obsolete by now…), coaxial copper cables for video and radio equipment, cat-5 or cat-6 cables for connecting Wi-Fi routers, desktop computers, servers, printers, scanners, etc. Communication may even run on the 220 V power supply lines by means of power-line-communication (PLC) units. This jungle of networks complicates the installation, maintenance and upgrading of services as well as the interactions among these networks. Optical fiber is a broadband medium which can carry many services independently of each other, making it an ideal candidate to unite all of these into a single network.

It is fully up to the user which network(s) he wants to have inside a house and he is not restricted by public network operators. However, silica single-mode fiber, as used in FttH lines, cannot easily be handled by unskilled users; this is brittle and needs high-precision tools to join two fibers. Two decades ago, initiated by Djan Khoe, we had therefore already started to investigate plastic optical fiber (POF) which features a large light-guiding core as well as high ductility. POF is therefore easy to install in a do-it-yourself fashion. Due to its relatively large losses, its use is restricted to short links of a few tens of meters only, but this is sufficient in many home scenarios. It also has a limited bandwidth due to its large core. We have investigated advanced multitone signal processing techniques and managed to still get Gigabit/s Ethernet speeds over indoor links with these [21]. Through spectrum multiplexing, we could even combine these data signals with LTE-A multiband radio signals in a large-core POF [22]. My colleagues Eduward and Henrie are continuing the good work in this research domain.

Wireless indoor networks

Increasingly, the user wants to not be bound by a wire, and indoor wireless communication by means of Wi-Fi and Bluetooth technologies is becoming more abundant. This is also driven by the upcoming Internet of Things wherever more home appliances need to be connected wirelessly. Just after I joined TU/e, we started to explore how we could combine the best of two worlds: freedom of movement through wireless connectivity enabled by radio techniques such as Wi-Fi and Bluetooth, and transparent broadband connectivity throughout the whole house by means of a fiber backbone network.

We started radio-over-fiber research in 2001. In order to transport high-frequency radio signals over bandwidth-limited indoor large-core fiber, I proposed a technique which we called 'optical frequency multiplying' [23][24]. As illustrated in Fig. 9, this is based on modulating the optical frequency of a laser diode by means of an external phase modulator with a low-frequency electrical carrier signal, which is relatively easy to do. Next, the frequency-modulated optical signal (which contains many harmonics of the carrier frequency) is run through an optical frequency-to-intensity converter, e.g., a simple Mach-Zehnder Interferometer, and the signal is subsequently transported via a dispersive fiber link to an optical intensity-detecting photodiode. A lot of higher harmonics are present in its electrical output signal, out of which the desired high-frequency radio carrier can be distilled. This technique, which we patented [24], can generate an extremely pure radio carrier wave at mm-wave frequencies, which can thus carry high data rate radio signals. This is dispersion-robust, so can readily be applied in dispersive indoor multimode fiber networks [25]. Moreover, the antenna station is fairly simple

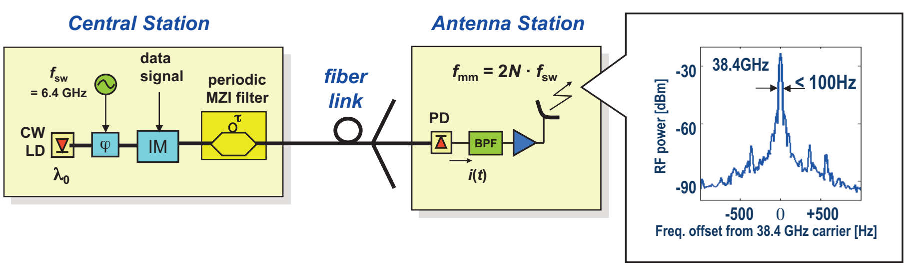


Fig. 9. The optical frequency multiplying technique for radio-over-fiber systems.

as all of the difficult high-frequency radio signal processing is done in the central station. To prove its feasibility, we generated a microwave carrier of 38.4 GHz with a linewidth too small to measure (<100Hz), notwithstanding the laser diode's linewidth of several MHz. We managed to carry 120 Mbit/s in a 64-QAM format over 4.4 km of graded-index multimode fiber and even over POF [26].

Such dispersion-robust radio-over-fiber techniques are very useful for flexibly routing radio signals to antenna sites which are located at different distances from the central station. The routing can then be optimized depending on the actual traffic at those sites, so can offer just-in-time 'capacity-on-demand'.

The demand for wireless connectivity is growing very quickly, fueled by the emergence of all kinds of broadband services via the internet and by the increasing numbers of mobile devices. According to recent (July 2021) market data [27], more than 92% of users use a mobile device for internet access in addition to the laptop and desktop computer. About 67% of the world's population of 7.9 billion people have a mobile phone and 57% use social media. These numbers are increasing rapidly. Wireless networks are becoming exhausted and novel techniques are needed to prevent a capacity collapse.

It is well-known that shrinking the size of the individual wireless cells in a network (while each cell can deliver a certain capacity) is probably the only way to meet the exponential growth of capacity demand. By halving the cell size, one actually doubles the network's capacity. There is hence a clear trend in radio wireless networks towards cell densification, i.e., by creating picocells. In order to avoid the need for huge amounts of antennas, each antenna should send multiple beams with each beam covering a picocell. As a result, even a room may be partitioned into multiple picocells, as illustrated in Fig. 10. By using narrow optical beams, as will be discussed later, even more picocells can be created and at smaller sizes. Moreover, for the ease of installation and maintenance, the antenna sites should be as simple as possible. Radio-over-fiber techniques which enable the remote generation and processing of radio signals are therefore attractive.

In radio technology, phased array antennas are well-known for shaping and steering high-frequency radio beams. A phased array antenna consists of many antenna elements which each emit a radio wavefront and, by adjusting the phase differences between the antennas, they collectively create a radio beam with a tailored shape which points in a particular direction. This technique works particularly well for mm-wave radio beams. However, it requires delicate high-

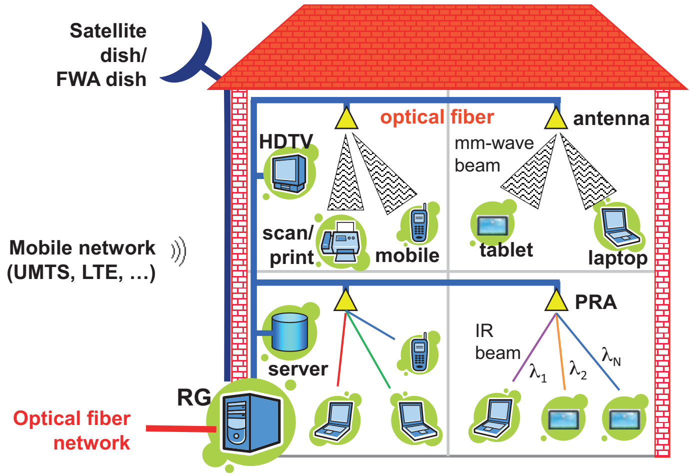


Fig. 10. Indoor wireless services delivered by steerable (mm-wave or optical) beams.

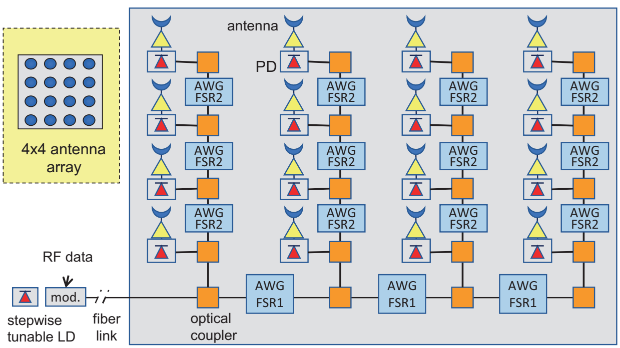
frequency tunable electronic phase shifters. Optical techniques can also help here: we devised an optical circuit which can create the required delays between the antenna elements by switching among on-chip optical delay lines. As illustrated in Fig. 11.b, the key element is a wavelength-routing circuit (AWG, arrayed waveguide grating) which directs an incoming optical signal to one of its output ports depending on the wavelength of the signal. Next, the signal runs from this output port through a delay line of a specific length to one of the AWG's input ports again. Due to the internal symmetry of the AWG, it subsequently appears at the common output port, but has in the meantime experienced a time delay in the wavelength-specific feedback loop.

We configured a matrix of such wavelength-tunable true-time-delay blocks with the proper interleaved wavelength characteristics in the columns and rows, as shown in Fig. 11.a. A two-dimensional phased antenna array can thus be created, of which the beam can be stepwise steered in two dimensions just by changing the wavelength of the incoming optical signal. The optical signal which carries the radio-modulated data is generated remotely in a wavelength-switchable laser diode transmitter and this optical signal is fed by fiber to the beam steering antenna station. My colleague Zizheng Cao (Pang) has done great PhD research work on this [28]. The delay unit for a basic 2×2 phased array antenna has been realized in a silicon-on-insulator photonic integrated circuit shown in Fig. 11.c and measurements confirmed its broadband wavelength-switchable delay characteristics.

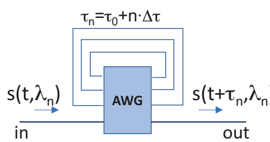
In this concept, it may be noted that multiple beams can be steered individually and simultaneously in different directions. The steering is controlled remotely simply by switching wavelengths, not requiring comprehensive control techniques at the antenna site itself. This can facilitate the operation and maintenance of advanced high-capacity wireless networks, as will increasingly be needed in 5G and beyond-5G systems.

Other tunable optical delay structures have also been investigated for a phased array antenna, such as thermally-tunable optical micro-ring resonators; these are more power-hungry, need more comprehensive control lines and their beam steering control is slower.

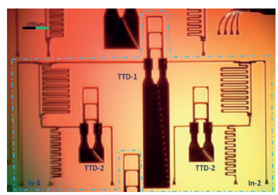
My colleague Eduward is continuing this research track, from which several PhD students have already graduated.



a. true-time-delay broadband 2D beam steerer



b. stepwise λ-tunable delay line



c. 2×2 tunable delay matrix

Fig. 11. Two-dimensional radio beam steering by an optically-controlled phased array antenna.

Optical wireless communication

Radio wireless technologies such as Wi-Fi and 5G are encountering more and more challenges in meeting the fast-growing demands for wireless connectivity. Moving to picocells with beam steering and more comprehensive modulation formats can offer some relief, but the radio spectrum needs to be extended besides that. The mm-wave domain, such as the 5764 GHz band, is being exploited already and research is now moving upwards to the THz domain.

A major step forward in wireless capacity can also be made here through optical techniques: the optical spectrum of visible light from 400 to 700 nm offers 320 THz of bandwidth and the infrared spectrum from 1500 to 1600 nm also offers a large 12.5 THz, so many orders of magnitude more bandwidth than is available at radio frequencies. Moreover, light can easily be tailored into narrow beams just by using passive lenses, which is far less complicated than tailoring radio beams with phased array antennas and can achieve a much higher equivalent antenna gain. Optical beams therefore significantly facilitate the creation of very small wireless cells and hold great promise for delivering high communication capacities with a high density in e.g. densily packed user areas such as meeting rooms, public transport cabins, industry 4.0 manufacturing halls, etc. [29][30].

Optical wireless communication (OWC) using visible light may be combined with illumination, e.g., LED lamps for indoor room lighting may also be modulated to emit data to the users in that room. This offers enhanced privacy with respect to Wi-Fi as the light does not penetrate walls and hence does not leak to the neighbors. Such so-called LiFi systems are already being introduced commercially by Signify (formerly Philips Lighting), among others. However, LED illumination systems are typically designed to illuminate a large area, so do not create picocells, and the output light is shared by multiple users in the room. Moreover, LEDs for illumination are designed for high-power efficiency, not for large modulation bandwidth. Both aspects therefore limit the capacity which can be provided to every user to a similar amount as Wi-Fi systems.

We started to investigate the use of narrow optical beams for OWC in 2012 [31][32]. With this technology, the beams bring the signals to users individually and therefore the users do not need to share a beam. This brings a number of distinct advantages with respect to Wi-Fi and LiFi. Each user can get a guaranteed high capacity, comparable or theoretically even higher than what a fiber can offer (as a beam does not suffer from the waveguide dispersion in a fiber). Each user gets virtually his own fiber without being tied to a fiber. Moreover, high privacy is assured as neighboring users cannot intercept the beam. Relatively large distances can be bridged as the beams hardly diverge. The beams are directed to users only when and where needed, so this concept is also very energy-efficient – no signal energy is wasted. This yields a high link power budget which enables a high data rate connection. And in contrast to Wi-Fi, for example, the optical communication links cannot be disturbed by external electromagnetic fields.

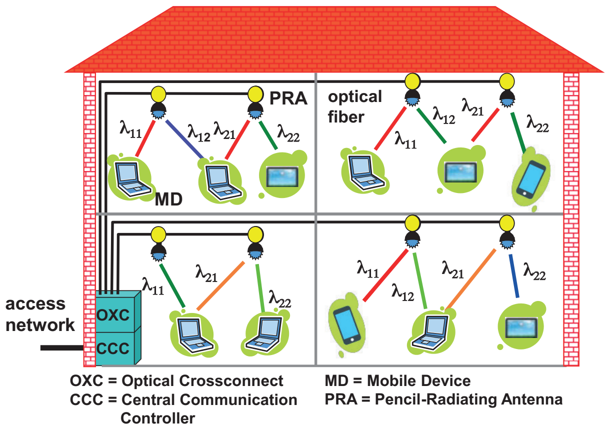
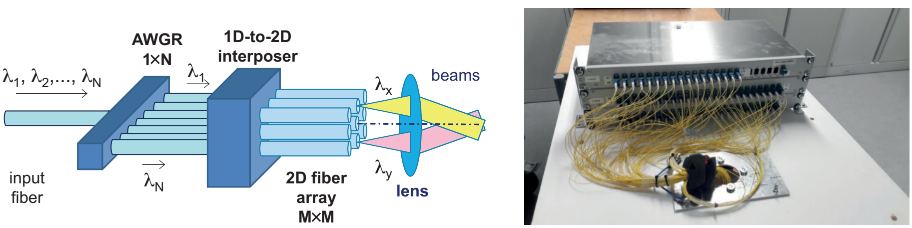


Fig. 12. Breaking wireless barriers: free-space beam-steered optical communication in the BROWSE concept.

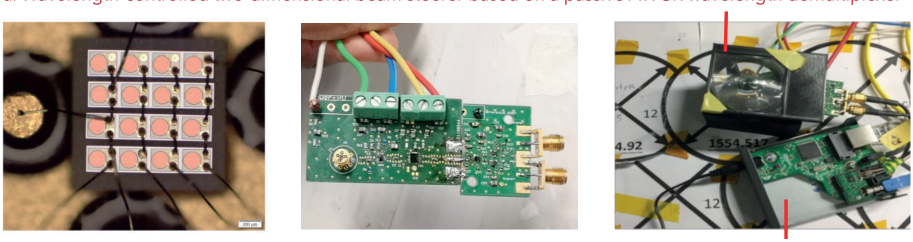
I received an Advanced Investigator Grant (the most prestigious personal grant) from the European Research Council to investigate this concept and named it 'BROWSE - Beam-steered Reconfigurable Optical-Wireless System for Energy-efficient communication' [31]. As illustrated for an indoor scenario in Fig. 12, multiple beams connect individual devices such as laptop computers, smartphones, tablets, video screens, etc. in each room. A passive unit on the ceiling (PRA – pencil radiating antenna) uses diffractive optical techniques. It is thus able to send a beam to a device in a specific two-dimensional direction depending on the beam's wavelength. Every room has two or more PRAs so that any blocking of a beam by an interrupting object or person can be circumvented by launching another beam from the other PRA to the device. The PRAs are connected to an internal optical fiber backbone network which can readily carry the many beam signals at their respective wavelengths. A remote unit inside each room or centrally located in the building can direct the signals to the respective PRAs; it also contains the wavelength-tunable transceivers which emit and steer the beams. As the wavelength signal controls the direction of a beam as well as carries the data information, it actually acts as an embedded control channel. So, no separate bookkeeping of which control channel belongs to which data channel is needed, thus greatly facilitating the network's management and control processes.

We explored the BROWSE concept with a great team of PhD students and postdocs. The research scope is quite multi-disciplinary: it involves optics as well as electronics, network routing and control techniques for solving the challenges of beam shaping and steering, the user localization needed for adequate beam steering, optical beam receivers with a large bandwidth and wide angle-of-view such that a delicate alignment of the user devices is not needed, and network control software for the signal routing.

We designed and built laboratory setups to validate this concept. It can offer a huge wireless capacity; we realized, for example, a system which can bring 80 channels at 112 Gbit/s each [33], i.e., an aggregate capacity of 8.96 Tbit/s from a single PRA, which is orders of magnitude more than a radio wireless router can bring. Fig. 13 shows some examples of the key system modules we created and



a. Wavelength-controlled two-dimensional beam steerer based on a passive AWGR wavelength demultiplexer



b. Optical wireless Gigabit/s Ethernet receiver with wide field of view based on 2D matrix of photodiodes

Fig. 13. Some key system modules.

which have been patented: a module which is fed from a single fiber and can steer up to 128 beams individually in two-dimensional angular directions depending on their wavelength [34][35] and a broadband receiver module with a large field of view which is equipped with a two-dimensional matrix of photodiodes [36], a Fresnel lens with large numerical aperture and a media converter providing a Gigabit/s Ethernet interface to e.g. a laptop computer [37][38][39].

Fig. 14 shows an implementation of our laboratory setup, with which we showed the wireless streaming of high-definition video films in the Gigabit Ethernet format to closely spaced users [38][39]. We also showed passive device localization techniques by means of cheap optical retro-reflectors [40], as well as active ones with optical tags at the device and camera observation [41][42]. In the demonstrator, we validated the system's operation with two receivers; the system can host up to 128. Next steps towards more compact modules using photonic integration are being pursued, as well as further sophistication of the system's

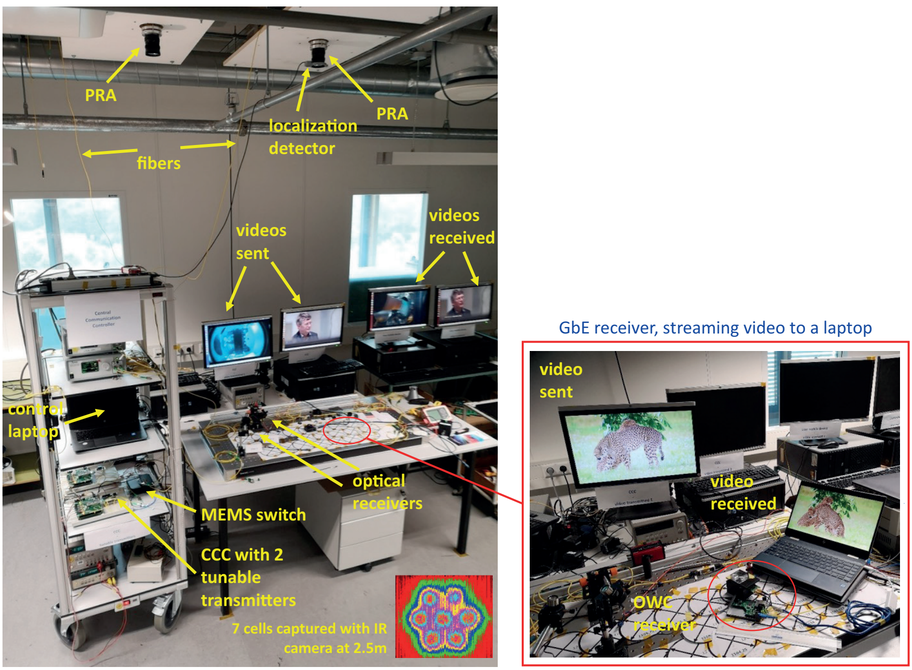


Fig. 14. Our laboratory demonstrator of an optical wireless communication system providing the transfer of high-definition video streams to closely spaced user devices.

control and bi-directional operation. My colleagues Eduward, Pang and Joanne are actively pushing this track further.

Moreover, we are at the verge of a new NWO Perspektief program 'Optical Wireless Superhighways', which I am happy to lead together with Prof. Eberhard Gil of TU Delft, including for some time beyond my retirement. It will explore the opportunities of OWC at all length scales, ranging from ultra-long links between satellites to short links within indoor rooms. In this program, researchers from TU/e, TU Delft, the University of Twente, the University of Leiden and the Free University of Amsterdam and a range of industrial partners will work closely together.

Optical wireless is right around the corner. It is remarkable that optical communication itself actually started with optical wireless: in ancient history, the Greeks relayed the news of the falling of Troy to Athens by means of fires on mountain tops. Alexander Graham Bell and his assistant Charles Sumner Tainter invented the photophone in Feb. 1880 and Bell considered this as his most important invention. Ships use wireless communication between them via morse code with optical signal lamps. Today's research on optical wireless communication may be seen as an exciting continuation of this journey, expanding it from its historical embryonic start into a powerful future of pervasive optical communication. Moreover, the Netherlands has been the cradle of Wi-Fi and Bluetooth, and our BROWSE technology may prove to be another successful wireless technology from the Netherlands.

Final words and thanks!

With this valedictory lecture, I hope that you have gotten a glimpse of the great potential of optical communication, not only for its original goal of bridging long distances at a high capacity but also for bringing access to the information highway to individual users. In these days of COVID-19, hopefully soon to be left behind us, we have learned how valuable it is to be connected to each other - not only for work but also for our social lives. Despite operating behind the scenes and not being as visible as electric cars, windmills and solar panels, optical communication systems have brought and are bringing huge benefits to our society. Without optical communication systems, there would not be the internet as we know it and working at home as well as meeting each other remotely (as we have frequently done in these lockdown times) would not have been possible. Also, wireless communication as we know it – from Wi-Fi, 3G, 4G, 5G to their follow-ups – depend on optical communication networks to feed them. It is not either fiber communication or wireless communication; it is the marriage of both of them which builds our communication world.

For me, it has been an enormous pleasure to work in this dynamic field of optical communication and to have been involved from its very early beginnings in the '70s. Doing your work with pleasure makes it light, as the title of my lecture says. Moreover, I hope that you have appreciated what optical communication can bring and how powerful it is: light really works, as the title of my lecture says as well…

But all of this would not have been possible without the many people I have worked with and who have supported me. "Many hands make the work light", as the saying goes – another underlining of the 'light work' in the title. So let me express my heartfelt thanks to these many people with the risk, of course, that some are not mentioned (my sincere apologies for that in advance…).

First, let me thank the Executive Board of our University, presently represented by Frank Baaijens, Robert-Jan Smits, Nicole Ummelen and Susanne van Weelden, for appointing me and putting trust in me during this journey of the past 20 years. TU/e is an inspiring environment where science and its applications meet intensely. My domain has been the domain of applied research, which somewhat anecdotically may be defined as 'research which is useful', 'onderzoek waar je wat aan hebt'. Originally coming from industry in what I sometimes call 'my first life', I grew up in applied research and, convinced of its value, I was most happy to pursue applied research in my 'second life' at the university. I therefore also want to thank the Board of our Department of Electrical Engineering, presently Bart Smolders, Jolie van Wevelingen, Marion Matters and Guus Pemen, for putting trust in me and allowing me to pursue exciting ideas in optical communication. Our department is a premier environment for applied research where many of my colleagues also have industrial roots. So I have really felt at home here and want to thank my many great colleagues in the EE department for the enjoyable cooperation. In my two terms as vice-dean, I got a profound insight into how nicely our EE community acts and works together and I am proud to have been a member of the EE team.

Let me also mention some people in particular, with the risk of overlooking others.

My first encounters with the wonderful world of optical communication started in my master's studies; I owe many thanks to Prof. Jan van der Plaats, who sadly passed away last year, and Prof. Wim van Etten, who both guided me on my first steps.

Next, I am indebted to my colleagues in industry: at Philips' Telecommunicatie Industrie, where Dr. Koen Mouthaan hired me in his group which built the first fiber-optic link in the Netherlands, at AT&T & Philips Telecommunications, at AT&T Network Systems and at Lucent Technologies-Bell Laboratories, where my many colleagues inspired me in the optical communication journey.

Prof. Ignas Niemegeers convinced me to make my first steps into the academic world as a part-time professor in his group at the University of Twente. There, I learned the good sides of academic life, working together with him, Prof. Sonia Heemstra de Groot and my part-time colleague Prof. Kees van Bochove of what at that time was KPN Research.

Prof. Djan Khoe was the one who brought me to TU/e; I also thank him very much for that. I had already known Djan for many years from the interactions we had with Philips Research when I worked in industry and his convincing arguments made me decide to come as a full-time professor to TU/e. And thanks to Djan, Joachim Wolter and Meint Smit, there was the strong COBRA institute, later superseded by the Institute for Photonic Integration, which was and is a perfect, unique environment to work in. It includes the full food chain of optical materials, photonic integrated circuits and optical systems and it offers my group and me the most fruitful environment to work in. Many thanks go to my colleagues in the institute, now chaired by Andrea Fiore. In order for this food chain to work, it must be noted that it is highly necessary for applied research to be done also after the basic research in order to arrive at a more mature level. For instance, if the photonic integrated circuits are not brought from their embryonic state in basic research to a more mature state in applied research, such circuits cannot be a solid base for basic research in optical systems. Likewise, PIC basic research must rely on some maturity of the optical materials. The new Photonic Integration Technology Center (PITC) can play a pivotal role in all of this.

Djan invited me to take over the chairmanship of our Electro-Optical Communication Systems group in 2004, which I gladly did. I really enjoyed leading the group and working with such an eminent group of colleagues for more than 16 years. They are not only experts in their fields but also became great friends.

During Djan's chairmanship, the group gained international stature. After I took over from him, the group's international reputation and visibility has been extended further. Our group became one of the strongest academic optical systems groups worldwide, I am proud to say. The European Conference on Optical Communication, the largest in Europe in this domain, was organized in Amsterdam in 1979 and 2001 and it was my great pleasure to organize it again in 2012. Each time, this was done in close cooperation with our Belgian colleagues and I owe many thanks to Prof. Peter Van Daele of University of Ghent for the enjoyable way we could do that together, including the ECOC in 2020 where Peter again showed himself to be a real 'Mister ECOC'.

My dear staff colleagues of the ECO group – Oded, who took over the chairmanship from me, Eduward, Pang, Huug, Chigo, Nicola, Patty, Henrie, Joanne, Sonia, George, Idelfonso, Simon, Frans, Johan, Ignas, Nico and, of course, my support and rock José – I am indebted to you all for the pleasant, collegial way we have worked together. Very sadly, we lost Harm in 2015; we owe him a lot for his great contributions to our research. Together, we faced many challenges in research and education, but we also enjoyed the many nice social events together with our PhD students and postdocs, such as our multicultural Christmas parties, 'beugelen' evenings, cooking course, outdoor trips, etc. You were and are an inspiring team with a great future ahead, I am sure.

I also thank the 36 PhD students I have graduated and the postdoctoral researchers, too many to include all their names here. They are the engines of our research, they create and disseminate the great results in the scientific world. Without them, everything would stay just as 'paperwork' and would fall short with respect to a lot of our ambitious goals in applied research. I am proud of the nice positions many of these students have acquired since then. They are often still great ambassadors for us and are valuable links for further bilateral cooperation in EC-funded projects, etc.

Last but not least, I want to thank my family and long-time friends who were at my side all the time. Thanks are due to my parents, who are unfortunately no longer with us; they encouraged me in my studies – my father was an electrical engineer too – and they built the basis for me upon which to develop myself.

And most of all, my thanks and love go to Annemie and my sons Martijn, Robin and Laurens. You are my ultimate source of inspiration. But you also pull me regularly back into daily reality, the world outside the work on optical technologies, scientific conferences, project meetings, university education and management tasks, etc. Annemie, you started to work in academia and transferred your enthusiasm for academic work to me. When we moved to the Eindhoven region, we exchanged positions: you went to industry, I to university. In this crossover, I learned a lot from you. With your incredible memory and surprising, original view on things, you always stimulate my curiosity. Above all, I would not have stood here without your love and support. I love you and I now hope and trust that with lots of love and time I can make it up to you for all the work schedules which were often so very busy up to now…

Ik heb gezegd.

References

1. A.M.J. Koonen, A.C. van Bochove, "Netwerken in een ander licht," joint inaugural lecture, 14 Oct. 1993, University of Twente, https://ris.utwente.nl/ws/files/155010526/Koonen1993netwerken.pdf .
2. Submarine Cable Map https://www.submarinecablemap.com/ .
3. A.M.J. Koonen, "Multiwavelength Add/Drop Multiplexer", US Patent No. 5,751,456, filed 20 Feb. 1996; issued May 12, 1998.
4. Fiber-optical submarine cables, https://en.wikipedia.org/wiki/Submarine_communications_cable ; https://spectrum.ieee.org/submarine-cable-goes-for-record-144000-gigabits-from-hong-kong-to-la-in-1-second#toggle-gdpr .
5. Ton Koonen, Henrie van den Boom, Anthony Ng'oma, Idelfonso Tafur Monroy, Giok-Djan Khoe, "Integrated-services in-building POF networks using novel signal multiplexing methods," *Proc. 11th International Conference on Plastic Optical Fibers (POF 2002)*, 18-20 Sep. 2002, Tokyo, vol. 1, pp. 87-90.
6. H.-S. Chen, H.P.A. van den Boom, A.M.J. Koonen, "30-Gb/s 3 x 3 optical mode group-division-multiplexing system with optimized joint detection," *IEEE Photonics Technology Letters*, vol. 23, no. 18, pp. 1283-1285, 2011.
7. P.J. Winzer, "Making spatial multiplexing a reality," *Nature Photonics*, vol. 8, pp. 345-348, May 2014.
8. R.G.H. van Uden, R. Amezcua Correa, E. Antonio Lopez, F.M. Huijskens, C. Xia, G. Li, A. Schuelzgen, H. de Waardt, A.M.J. Koonen, C.M Okonkwo, "Ultra-high-density spatial division multiplexing with a few-mode multicore fibre," *Nature Photonics*, vol. 8, no. 11, pp. 865-870, Oct. 2014.
9. A.M.J. Koonen, N. Yan, J.J.V. Olmos, I.T. Monroy, C. Peucheret, E. van Breusegem, E. Zouganeli, "Label-controlled optical packet routing–technologies and applications," *IEEE J. of Selected Topics in Quantum Electronics*, vol. 13, no. 5, pp. 1540-1550, 2007.
10. Ton Koonen, "Fiber to the Home/Fiber to the Premises: what, where, and when?", *IEEE Proceedings*, vol. 94, no. 5, May 2006, pp. 911-934.
11. A.M.J. Koonen, "A compact wavelength demultiplexer using both interference filters and a diffraction grating," *Proc. 7th European Conf. on Optical Communication*, Copenhagen, 8-11 Sep. 1981, paper 8.5.
12. A.M.J. Koonen, "Optical wavelength demultiplexer", US Patent 4.723.829, 9 Feb. 1988 (Ned. Octr. 8104124, 7 Sep. 1981).
13. A.M.J. Koonen, A. Wismeijer, "Optical devices for wavelength division multiplexing systems," *Philips Telecommunication Review*, vol. 40, no. 2, July 1982, pp. 102-110.
14. BIGFON: wideband optical fibre local communication network trial by Deutsche Bundespost in 1981-1988, https://de.wikipedia.org/wiki/BIGFON
15. A.M.J. Koonen, "Dynamic Reconfiguration of a Wireless Network Using Flexible Wavelength Multiplexing", US Patent No. 5,978,117, filed Aug. 29, 1997, issued Nov. 2, 1999.
16. Ton Koonen, Theo Muys, Chris van der Plaats, Sonia M. Heemstra de Groot, H.J.H.N. Kenter, Ignas G.M.M. Niemegeers, Frans N.C. Slothouber, "TOBASCO: An innovative approach for upgrading CATV fibre-coax networks for broadband interactive services," *IEEE Communications Mag.*, vol. 35, no. 4, Apr. 1997, pp. 76-81.
17. A.M.J. Koonen, C.A.M. Steenbergen, A.W.L. Janssen, J.S. Wellen, "Flexibly reconfigurable fiber-wireless network using wavelength routing techniques: the ACTS project AC349 PRISMA," *Photonic Network Communications*, vol. 3, no. 3, 2001, pp. 297-306.
18. A.M.J. Koonen, "Re-configurable fibre wireless network", US Patent No. 6,674,966, filed Oct. 12, 1999, issued Jan. 6, 2004.
19. A.M.J. Koonen, C.A.M. Steenbergen, J.S. Wellen, C. Nicolas, D. Delprat, E. Weiss, M.M.F. Adamy, "Dynamically reconfigurable WDM hybrid fibre access network for IP-based services with various QoS demands," *Proc. of the European Conference on Networks and Optical Communications 2000 (NOC 2000),* June 6-9, 2000, Stuttgart, pp. 134-140.
20. P.J. Urban, B. Huiszoon, R. Roy, M.M. de Laat, F.M. Huijskens, E.J. Klein, G.-D. Khoe, A.M.J. Koonen, H. de Waardt, "High-bit-rate dynamically reconfigurable WDM-TDM access network," *J. of Optical Communications and Networking*, vol. 1, no. 2, July 2009, pp. A143-A159.
21. S.C.J. Lee, F. Breyer, S. Randel, H.P.A. van den Boom, A.M.J. Koonen, "High-speed transmission over multimode fiber using discrete multitone modulation," *J. of Optical Networking*, vol. 7, no. 2, Feb. 2008, pp. 183-196.

22. F. Forni, Y. Shi, H.P.A. van den Boom, E. Tangdiongga, A.M.J. Koonen, "LTE-A compliant multi-band radio and gigabit/s baseband transmission over 50m of 1mm core diameter GI-POF for in-home networks," *Electronics Letters*, vol. 52, no. 9, Mar. 2016, pp. 738-740.
23. A.M.J. Koonen, M. Garcia Larrode, "Radio-over-MMF techniques - Part II: microwave to millimeter-wave systems," *J. of Lightwave Technology*, vol. 26, no. 15, Aug. 2008, pp. 2396-2408.
24. A.M.J. Koonen, "Werkwijze en stelsel voor het via een multi-modus optische vezel overdragen van microgolfsignalen" (Method and system for transport of microwave signals via a multimode optical fibre), Dutch patent NL1019047, issued April 2, 2003.
25. M. Garcia Larrode, A.M.J. Koonen, "Theoretical and experimental demonstration of OFM robustness against modal dispersion impairments in radio over multimode fiber links," *J. of Lightwave Technology*, vol. 26, no. 12, June 2008, pp. 1722-1728.
26. A. Ng'Oma, I. Tafur Monroy, J.J. Vegas Olmos, A.M.J. Koonen, G.-D. Khoe, "Frequency up-conversion in multimode fiber-fed broadband wireless networks by using agile tunable laser source," *Microwave and Optical Technology Letters*, vol. 41, no. 1, Apr. 2004, pp. 28-30.
27. Datareportal, "Digital around the world," https://datareportal.com/global-digital-overview
28. Z. Cao, X. Zhao, F.M. Soares, N.M. Tessema, A.M.J. Koonen, "38-GHz millimeter wave beam steered fiber wireless systems for 5G indoor coverage: architectures, devices, and links," *IEEE J. of Quantum Electronics*, vol. 53, no. 1, Feb. 2017, 9 pp.
29. A.M.J. Koonen, "Indoor optical wireless systems: Technology, trends, and applications," *J. Lightw. Technol*., vol. 36, no. 8, Apr. 2018, pp. 1459–1467.
30. A.M.J. Koonen, K.A. Mekonnen, Z. Cao, F. Huijskens, N.-Q. Pham, E. Tangdiongga, "Ultra-high-capacity wireless communication by means of steered narrow optical beams," *Philosoph. Trans. A*, Oct. 2019, 19 pp.
31. A.M.J. Koonen, C.W. Oh, K. Mekonnen, Z. Cao, and E. Tangdiongga, "Ultra-high capacity indoor optical wireless communication using 2D-steered pencil beams," *J. Lightw. Technol.*, vol. 34, no. 20, Oct. 2016, pp. 4802–4809.
32. A.M.J. Koonen, P.G.M. Baltus. A. Liotta, "Two-dimensional optical beam steering module", US Patent 9246589, issued Jan. 26, 2016, filed Jan. 18, 2012.
33. F. Gomez-Agis, S.P. van der Heide, C.M. Okonkwo, E. Tangdiongga, A.M.J. Koonen, "112 Gbit/s transmission in a 2D beam steering AWG-based optical wireless communication system," in *Proc. ECOC2017*, *Göteborg*, *17–21 Sep. 2017*, *paper Th.2.B.1*.
34. A.M.J. Koonen, F. Gomez-Agis, F.M. Huijskens, and K.A. Mekonnen, "High-capacity optical wireless communication using two-dimensional IR beam steering," *J. Lightw. Technol.*, vol. 36, no. 19, Oct. 2018, pp. 4486–4493.
35. A.M.J. Koonen, "Two-dimensional optical beam steering module," Patent PCT/EP2017/080716, published June 7, 2018, priority date Nov. 29, 2016.
36. A.M.J. Koonen, "Receiver for optical wireless communication with large aperture and wide angle of view," Patent PCT/EP2020/080594, published May 6, 2021, priority date Oct. 31, 2019.
37. A.M.J. Koonen, K.A. Mekonnen, F.M. Huijskens, Z. Cao, E. Tangdiongga, "Novel broadband OWC receiver with large aperture and wide field of view", *Proc. ECOC2020*, Brussels (on-line), Dec. 2020, paper Tu2G.6.
38. Ton Koonen, Ketemaw Mekonnen, Frans Huijskens, Ngoc Quan Pham, Zizheng Cao, Eduward Tangdiongga, "Optical Wireless GbE Receiver with Large Field-of-View," accepted for *ECOC 2021*, Bordeaux, 13-16 Sep. 2021, paper Th1B.6.
39. Ton Koonen, Ketemaw Mekonnen, Zizheng Cao, Frans Huijskens, Ngoc Quan Pham, Eduward Tangdiongga, "Beam-Steered Optical Wireless Communication for Industry 4.0," *IEEE J. of Selected Topics in Quantum Electronics*, vol. 27, no. 6, Nov./Dec. 2021, 10 pp.
40. A.M.J. Koonen, K.A. Mekonnen, F.M. Huijskens, N.-Q. Pham, Z. Cao, E. Tangdiongga, "Fully passive user localization for beam- steered high-capacity optical wireless communication system," *J. Lightw. Technol.*, vol. 38, no. 10, May 2020, pp. 2842-2848.
41. Ngoc Quan Pham, Ketemaw Mekonnen, Eduward Tangdiongga, Ali Mefleh, Ton Koonen, "User Localization and Upstream Signaling for Beam-Steered Infrared Light Communication System," *Phot. Techn. Lett.*, vol. 33, no. 11, June 2021, pp. 545-548.
42. Ngoc Quan Pham, Ketemaw Mekonnen, Eduward Tangdiongga, Ali Mefleh, Ton Koonen, "Efficient Mobility Management for Indoor Optical Wireless Communication System," *Phot. Techn. Lett.*, vol. 33, no. 17, Sep. 2021, pp. 939-942.

Curriculum Vitae

Prof. Ton Koonen was appointed as a full-time professor of 'Breedbandige netwerken' (Broadband Networks) at the Department of Electrical Engineering at Eindhoven University of Technology (TU/e) on January 1, 2001.

Ton Koonen (1954) received an MSc cum laude in Electrical Engineering from TU/e in 1979. He subsequently worked in applied research at Philips' Telecommunicatie Industrie (1979-1984), AT&T Network Systems (1984-1987), and Lucent Technologies–Bell Laboratories (1994-2000). Ton was a part-time professor at the University of Twente (1991-2000) and joined TU/e in January 2001 as a full-time professor. He chaired the Electro-Optical Communication Systems group (2004-2021). He was vice-dean of the Department of Electrical Engineering (2012-2020) and Scientific Director of the Institute for Photonic Integration (formerly COBRA; 2016-2019). Ton is a Bell Labs Fellow (1998, first one in Europe), IEEE Fellow (2007), Fellow of the Optical Society of America (2013) and High-level Visiting Scientist at Beijing University of Posts and Telecommunications (111 Program, 2018-2023). He is a Principal Investigator in the Dutch Gravitation programs 'Center for Integrated Nanophotonics' and 'Networks' (both 2013-2023).
He received the ICTRegie Award (2009). In 2012, he received the prestigious Advanced Investigator Grant of the European Research Council on optical wireless communication, followed by a Proof-of-Concept Grant in 2018. With this research, Ton was one of the six finalists in the national Huibregtsen prize competition in 2018.
Ton initiated and managed a wide range of national and international projects in optical systems research and secured more than € 30M in funding. He (co)authored more than 750 conference and journal papers.

Colophon

Production
Communicatie Expertise
Centrum TU/e

Cover photography
Bart van Overbeeke
Photography, Eindhoven

Design
Grefo Prepress,
Eindhoven

ISBN 978-90-386-5365-5
NUR 959

Digital version:
www.tue.nl/lectures/

Visiting address
Building 1, Auditorium
Groene Loper, Eindhoven
The Netherlands

Navigation
De Zaale, Eindhoven

Postal address
PO Box 513
5600 MB Eindhoven
The Netherlands
Tel. +31 (0)40 247 9111
www.tue.nl/map

EINDHOVEN
UNIVERSITY OF
TECHNOLOGY