

Tijdschrift van het NERG

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Het NERG is een wetenschappelijke vereniging die zich ten doel stelt de kennis en het wetenschappelijk onderzoek op het gebied van de elektronica, signaalbewerking, communicatie- en informatietechnologie te bevorderen en de verbreiding en toepassing van die kennis te stimuleren.

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De jaarlijkse contributie bedraagt voor gewone leden € 43,- en voor studentleden € 24,-. Bij automatische incasso wordt € 2,- korting verleend. Gevorderde studenten aan een uni-

versiteit of hogeschool komen in aanmerking voor het studentlidmaatschap. In bepaalde gevallen kunnen ook andere leden, na overleg met de penningmeester voor een gereduceerde contributie in aanmerking komen.

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Het tijdschrift verschijnt vijf maal per jaar. Opgenomen worden artikelen op het gebied van de elektronica, signaalbewerking, communicatie- en informatietechnologie. Auteurs, die publicatie van hun onderzoek in het tijdschrift overwegen, wordt verzocht vroegtijdig contact op te nemen met de hoofdredacteur of een lid van de Tijdschriftcommissie.

Voor toestemming tot overnemen van (delen van) artikelen dient men zich te wenden tot de tijdschriftcommissie. Alle rechten berusten bij de auteur tenzij anders vermeld.

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ISSN 03743853

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Voor U ligt het eerste nummer van het Tijdschrift van het NERG van 2010. Het afgelopen jaar is ons tijdschrift helaas niet verschenen. Ook de jaren daarvoor lag het aantal uitgebrachte nummers beneden het gewenste aantal. De belangrijkste oorzaak hiervan is de al enkele jaren bestaande onderbezetting van de tijdschriftcommissie. Voor dit jaar hebben we in ieder geval genoeg kopij voor twee nummers. Uiteraard kunnen we iedere versterking van de tijdschriftcommissie goed gebruiken. Vooral de correctie van taal- en spelfouten en het samenstellen van het proefschriftenoverzicht nemen veel tijd in beslag. Het eerste neemt de laatste tijd minder tijd in beslag

omdat veel van de recent in het tijdschrift gepubliceerde artikelen reeds elders gepubliceerd zijn.

Dit nummer zal ook het eerste zijn dat als elektronisch tijdschrift op de website geplaatst gaat worden. Het is de bedoeling dat leden m.b.v. hun loginnaam en password toegang hebben tot de individuele artikelen uit het tijdschrift. De papieren versie blijft vooralsnog gewoon bestaan.

Dit nummer opent met een algemeen artikel van Ton Koonen over glasvezeltechnologie. De aanleiding voor dit artikel is het feit dat de Japanner Charles Kuen Kao in 2009 de Nobelprijs

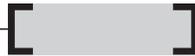
voor natuurkunde heeft gewonnen voor zijn pionierswerk op dat gebied. Het tweede artikel gaat ook over optische technologie en is geschreven door Bas Huiszoon. Voor zijn proefschrift, waar zijn artikel op gebaseerd is, kreeg hij op 15 april 2009 de Vederprijs uitgereikt. Verder bevat dit nummer het proefschriftenoverzicht 2007-2008. Ook hier is er dus sprake van enige achterstand. Helaas is het steeds moeilijker om de proefschriften van de Universiteit Twente te achterhalen. Het laatste artikel in dit nummer is van Maurice Kwakkernaat en gaat over het in beeld brengen van het gedrag van radiogolven in mobiele netwerken.



Nobel prize 2009 for Charles Kao, pioneer in optical fibres

Ton Koonen

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The world is pending on a tiny thread, a thread of glass. Optical fibre is vastly deployed all over the world, to carry our telephone conversations, computer data, TV signals, the internet with its exploding gamma of services, etc. Our economic, social and cultural activities would come to a standstill without the huge communication streams which the tiny silica glass fibre is able to carry. When Samuel Morse introduced the telegraph and Alexander Graham Bell the telephone, the world was dependent on copper wires. And still large parts of the communication networks are using copper, in particular the twisted-pair telephone lines and the coaxial cable CATV lines connecting the users' homes. Electrical signals get attenuated on the lossy copper lines, necessitating lots of amplifiers all over in the networks. The bandwidth of these lines is quite limited, and is running out of steam in view of the fast growing capacity needs of the internet. Moreover, as the world's resources are expiring, copper gets ever more expensive. Charles Kao, who was born in 1933 in Shanghai, and got his PhD degree in Electrical Engineering in the Imperial College London in 1965, recognized these shortcomings already in the mid 60's. He worked as an engineer in Standard Telephones and Cables (STC) in Harlow, UK, and there he developed his groundbreaking ideas of how to carry light with extremely low losses through glass fibre. He first presented his results in January 1966 in London to the Institute of Electrical Engineers (IEE).

Low-loss light guiding

The guiding of light in curved media was already observed much earlier, e.g. by noticing that in illuminated fountains light was guided by the curved water beams. The light guiding is actually realized by 'total internal reflection': light propagating in a material with a high refractive index is reflected at



Charles Kuen Kao
Nobel Prize in Physics 2009: "for groundbreaking achievements concerning the transmission of light in fibers for optical communication"

the interface with a medium with lower refractive index, provided that the incidence angle on this interface is larger than the critical angle. As this reflection is very efficient and causes negligible losses, light can be confined and guided through the water beam. Obviously more stable solutions than water beams are needed, so similar experiments were done with homogeneous threads of glass. Endoscopy could be done with many of these glass threads united in a single cable. However, small scratches and other irregularities at the surface of the glass destruct the total internal reflection process, and light leaks out. Hence the losses of such homogeneous threads were too high for guiding light over larger distances. Moreover, impurities in the glass itself contributed to the losses. Charles Kao came up with fused silica (silicon dioxide) as the perfect material for very low loss light guiding. And the fibre structure itself should not be a homogeneous thread, but should have an inner core having a high refractive index, surrounded by a glass cladding with a lower index. Thus the boundary was nicely protected and could serve as a reliable close-to-perfect mirroring surface for guiding the light beam. Kao's claim which he presented in 1966 was that, with fused silica

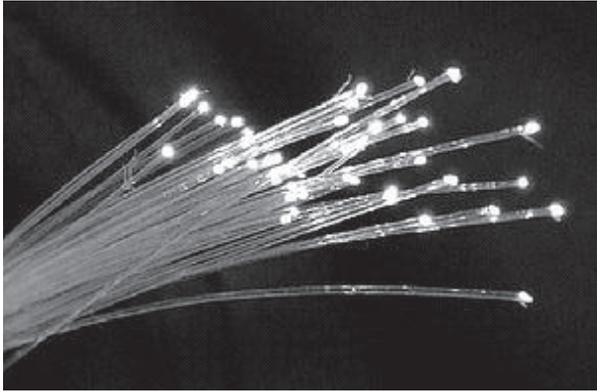


Fig. 1: Silica optical fibres (diameter 125 μm each).

glass and the core-cladding structure, losses of less than 20 decibels per kilometer should be feasible, i.e. more than 1% of the light power should still remain after propagation through 1 kilometer of fibre. In 1970, Keck and co-workers at Corning Glass in the US indeed demonstrated light guiding in such optical fibre with less than 20 dB/km loss.

Modern optical fibre has a standardized outer diameter of only 125 micrometer, within 1 μm . This is about the thickness of a human hair (see Fig. 1). Regarding attenuation, it has made a huge progress since its invention, while still following Kao's principles. It now conveys more than 95% of the light through 1 kilometer of fibre, i.e. it has a loss of less than 0.2 dB/km. This has only been possible by bringing the purity of the silica glass to the extreme, using precisely controlled environmental conditions, very sophisticated chemical vapour deposition techniques for building a structured perform, excluding every tiny amount of water, and drawing the preform into a very tightly controlled fibre.

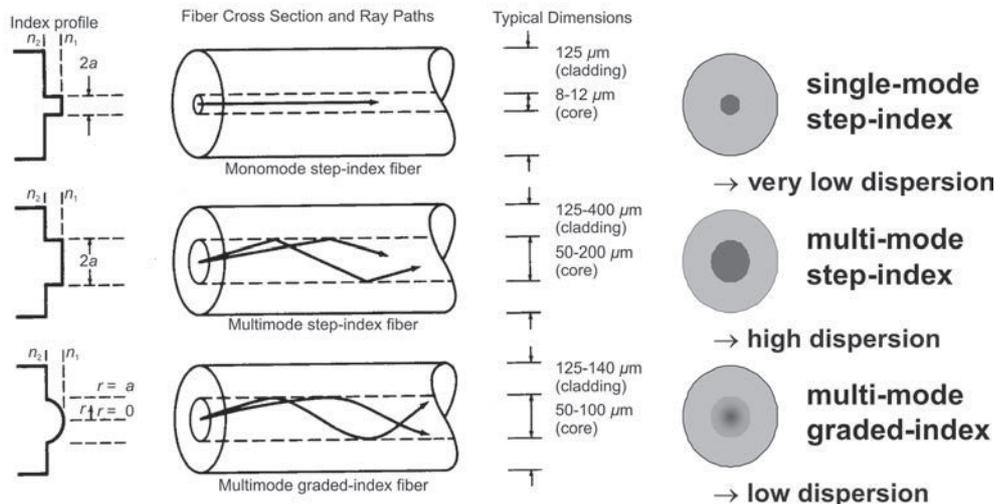
The diameter of the fibre's core has a major impact on the light guiding properties: when it is on the order of the wavelength, it can be shown that the fibre is able to guide light only in a single mode: hence it is called a single-mode optical fibre (see Fig. 2). When it is much thicker, many more modes can be guided: a multimode fibre. Each mode has a different propagation time; thus an optical pulse, which is guided by these modes, will get dispersed and is broadened when it arrives at the fibre's end. When pulses broaden, they cannot be put closely together anymore without serious overlap. Hence this modal dispersion phenomenon limits the rate at which pulses can be transmitted, so the bandwidth of the fibre. The modal dispersion can be reduced by accelerating the light rays which are making the larger excursions when travelling through the core, so by reducing the refractive index of the core towards the cladding, see Fig. 2. Such 'graded-index multimode fibre' shows a clearly larger bandwidth than its step-index counterpart. Obviously, a single-mode fibre shows hardly any pulse broadening, and thus has the ultimate bandwidth.

Single-mode fibre is by far the most wide-spread fibre type. Multimode fibre is only applied for shorter links, such as in in-building networks. Thanks to its larger core, it is easier to connect than single-mode fibre.

Dispersion and losses

The bandwidth of single-mode fibre is mainly limited by material dispersion (since the refractive index of the silica glass is slightly dependent on the wavelength) and by waveguide dispersion (since the electrical field spreads out from the core into

Fig. 2: Light guiding by optical fibres.



the cladding, and this spreading becomes larger at increasing wavelength). Material dispersion and waveguide dispersion have opposite signs, and can cancel each other. For silica glass, this happens at a wavelength of about $1.31 \mu\text{m}$, the so-called 'zero-dispersion wavelength'. At this wavelength, the fibre reaches its ultimate bandwidth, and the bandwidth of the whole fibre link is then only limited by the spectral purity of the laser transmitter.

The fibre's losses depend on the wavelength of the light, and reach their lowest value around $1.55 \mu\text{m}$, which is in the near infra-red. As Fig. 3 shows, the low-loss wavelength region of the fibre represents a huge optical frequency range, and thus an extremely large capacity for guiding telecommunication signals. A laser diode, which is another crucial element in an optical fibre communication link, can send light pulses at a very high repetition rate, at tens of giga-Hertz, but only occupies a tiny part of this optical frequency range. But many of these laser diodes, each operating at a slightly different optical frequency, can be put in parallel and thus together convey massive amounts of data. Using this so-called 'wavelength division multiplexing', in the laboratory transmission has been achieved with speeds exceeding 21 terabits per second. Such a capacity would allow that one half of the world's population can have a phone conversation with the other half, just through one tiny silica optical fibre as thick as a human hair!

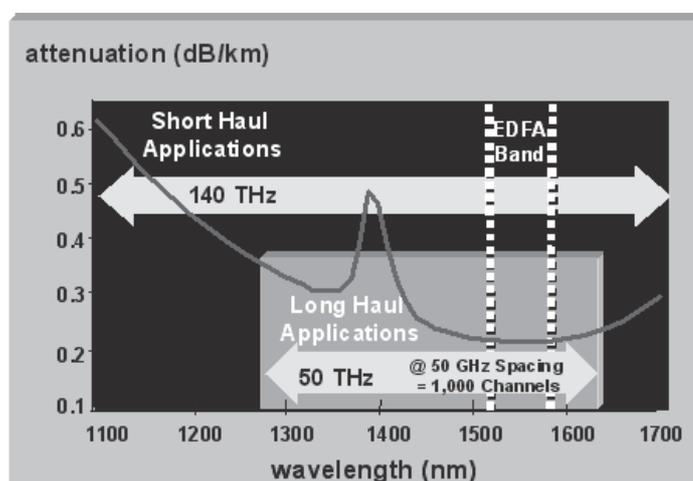
Nowadays optical fibre is installed all over the world. The total length amounts to some 1 billion kilometers, 25000 times the circumference of the earth! Many fibre links are connecting the continents together; e.g., the transatlantic links bridge

the ocean between Europe and North America, ca. 6000 km, and the transpacific links between the west coast of the US and Japan, ca. 9000 km, with an intermediate landing point in Hawaii. Although the fibre has very low losses, such distances cannot be bridged without amplification. The advent of the optical fibre amplifier, in particular the erbium-doped fibre amplifier (EDFA) was another landmark in the evolution history of optical communication systems. When doped with the rare earth material erbium which is brought into an excited state by optical pumping with another laser, the doped optical fibre can amplify optical signals directly without converting them first into electrical signals. Many wavelength channels can be amplified all-optically and simultaneously, which makes such an optical amplifier an essential component in long-haul wavelength-multiplexed systems.

Fibre-to-the-home and fibre-in-the-home

Whereas silica fibre has conquered telecommunication networks in the long-haul parts, spanning oceans, continents, but also countries and cities, the final drop to the user's home is in most places still on twisted-pair copper lines and/or coaxial copper cables. This final access drop is more and more becoming the bottleneck in offering high capacity to the user. Hence fibre is now increasingly being installed all the way to the homes in access networks, replacing the copper lines, and by virtue of its tremendous capacity hosting all the services offered by the copper media (triple play: video, voice, and data) and any service yet to come! In Japan, fibre-to-the-home has already outnumbered the copper twisted pair connections (the digital

Fig. 3: Attenuation of silica single-mode fibre.



subscriber line, DSL). And the US and many European countries are progressing in the same direction. Connection speeds to the home are typically 100 Mbit/s both to and from the home; in Japan, even 1 Gbit/s is introduced.

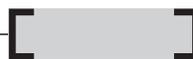
But Fibre to the Home is not the end game yet in the quest of bringing the ultimate communication highway to the user. After having reached the doorstep, the highway needs to be extended into the home, up to the devices of the user himself. Thus research is now being directed to optical fibre systems for in-home, where it becomes crucially important to make the system robust, and easy to install, preferably in a do-it-yourself fashion. Silica fibre is brittle and has to be installed with precision tools and by skilled personnel. As an alternative, plastic optical fibre (POF) is coming up, which can be made much thicker, and is ductile. This makes it much easier to handle and to install, even by unskilled persons. Its losses are by far not as low as those of silica fibre, but as in-home link lengths are short, that is not a show-stopper. Like the silica fibre proposed by Kao, also the POF has a core-cladding structure. Its large diameter causes a high modal dispersion, and thus severely limits its bandwidth for longer lengths. But again, lengths are short, and thus this is not lethal. Special techniques are being developed to convey Gbit/s data streams over POF networks. Also techniques are being investigated to carry microwave radio sig-

nals over the fibre in order to meet the user's needs for broadband wireless communication without having to put comprehensive microwave radio equipment everywhere.

So by pioneering optical fibre, Charles Kao has opened the road towards real broadband communication, where the sky is the limit, and light is shining into a bright future where we can communicate with each other without any borders!

About the author

Ton (A.M.J.) Koonen is a Full Professor at Eindhoven University of Technology, in the Electro-optical Communication Systems Group, being Chairman of this group since 2004. He worked for over 20 years in applied research in broadband telecommunication systems: as a member of technical staff at Philips Telecommunication Industry, as technical manager with Bell Laboratories in AT&T Network Systems and in Lucent Technologies. His current research interests include broadband communication technologies and networks, in particular fiber access and in-building networks, radio-over-fiber networks, and optical packet-switched networks. Prof. Koonen is a Bell Laboratories Fellow since 1998, an IEEE Fellow since 2007, and an elected member of the IEEE LEOS Board of Governors since 2007.



Met toestemming overgenomen uit Europhysics News, het blad van de European Physical Society, de Europese vereniging van natuurkundigen.

Layer 2 and 3 Contention Resolution and Radio-Over-Fiber in OCDMA PON for Transparent Optical Access in Personal Networks

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Abstract - In this paper, we analyze, for the first time, the eminent role of optical transparent networking in personal networks. We show how an optical access network mitigates many issues with respect to connectivity and mobility management. A concrete personal network user-scenario deduces requirements for such an architecture. A combination of passive optical network, optical code-division multiple access (OCDMA), and radio-over-fiber exhibits minimal cost and complexity because of centralized network control and management, resource sharing, and simplified network nodes. We enable transparent peer-to-peer communication between optical networking units in the OCDMA passive optical network subnet of the central office. We use, for the first time, simultaneously optical code-sense medium access control and optical code packet switching for contention resolution.

Index Terms - code-division multiaccess, optical code packet switching, optical fiber communication, personal area network, personal networks, wireless access networks, radio-over-fiber.

I. Introduction

As the bandwidth demands rise in wired and wireless networks, research efforts concentrate on the increase of optical transparency in the physical infrastructure and on the increase of capacity and range in the radio-frequency domain [1]-[6]. Ubiquitous network connectivity has become a commodity but puts strict requirements on the network. The access network is a bottleneck and a limiting factor in the network performance. Two

interesting global developments are observed in that field: on the one hand, the introduction of optical fiber in the local loop [7], [8], and on the other hand, individual subscribers increasingly carrying around their own short-range personal area network (PAN), which is enabled by Bluetooth or IEEE 802.15 [9]. Both developments enhance the user's experience with high available bandwidth and mobility. If the PAN (a truly mobile network) is taken as an entity, a personal network (PN) is defined by the PAN and the other, remote personal devices the PAN is connected with [10]. Hence a strong evolution is observed in both the fixed and wireless network domains. Even though optical fiber has proven to be the physical communication medium of the future, it does not naturally support the mobile behavior of devices forming a PN. The integration of both the optical and RF domains is a well-studied research topic, where the discussion is mainly focused on remote radio signal distribution via fiber, remote microwave carrier generation, and basic dynamic bandwidth distribution [11]-[13]. The personal network concept has much stronger requirements such as very fast discovery of remote personal devices and services that can only be fulfilled by an optical infrastructure [14], [15].

In this paper, we analyze, for the first time, how optical transparent networking plays an important and crucial role in personal networks. We propose an optical transparent access layer whereby the focus is on overall reduction of costs and com-

plexity through an efficient sharing of resources, simplified network nodes, and centralized network management. The architecture as such is based on passive optical networks (PONs), optical code-division multiple access (OCDMA), and radio-over-fiber (RoF). RoF techniques enable one to perform the access control and signal processing of a wireless system at the central node and to deliver transparently the radio signals to simplified radio access points (RAPs) via optical fiber. We have analyzed the integration of an RoF and OCDMA system. We propose transparent peer-to-peer communication between optical networking units in the PON subnet of the central office (CO). We present, for the first time, simultaneous optical code-division multiple access (MAC) and optical code packet switching for contention resolution.

The organization of this paper is as follows. First optical network transparency is reviewed in Section II and a three-layered personal archipelago of transparency is defined as the minimum amount of transparent fixed network domains required for a global connection. Section III analyses an optical access layer that supports user mobility in a heterogeneous landscape of wireless networks. The personal network concept and OCDMA are introduced in Sections IV and V. Section VI shows the integration of a hybrid system that employs OCDMA and the radio-over-fiber technique optical frequency multiplication (OFM). Section VII shows how to provide transparent peer-to-peer communication in the optical access layer. Furthermore, contention resolution is done via optically implemented collision detection and packet switching. This paper is concluded in Section VIII.

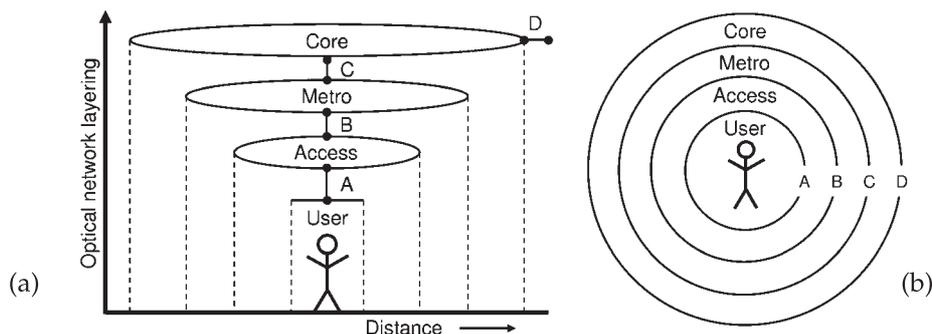
II. Optical network transparency

In this section, we review the definition of island-of-transparency and define a user's personal archipelago of transparency, which is used through-

out this paper. The optical wavelength is the main carrier in today's global network. Its path, however, is limited in range. In other words, the distance that can be reached on a single wavelength is restricted. This is commonly referred to as a lightpath [16]. Throughout the network, opaque optical-electrical-optical (OEO) or semitransparent wavelength conversion nodes interrupt the lightpath between different parts of the optical network. A special case is the access domain, which has the historically grown bandwidth bottleneck caused by the physical properties of the electrical media used. Optical access has reached a significant penetration ratio in only a few countries worldwide. Network segments are bounded in their optical transparency and, therefore, are denoted islands of transparency (IoTs). The IoTs prevent end-to-end transparency between global and local network connections. Operators strive for a reduction of these IoTs such that optical transparency is maximized to alleviate limitations in speed, complexity, and costs introduced by the opaque or semitransparent network nodes.

The area of an IoT can be enlarged by employing all-optical technologies. As a consequence, optical transparency has to be introduced in the access domain. If we consider a separate optical access layer, a personal archipelago of transparency (PAT) can be defined around each user. This is shown in Fig. 1 in an ideal situation where the physical fixed network domains access, metro, and core each constitutes an IoT. The solid borders indicate a transition between different domains. The islands are interconnected by nodes A through D. A network node is present to access the domains. A node can, for example, change the transmission technique, perform data routing, etc. The PAT domains in Fig. 1 match with a three-tiered Ethernet/IP architecture to design a global (enterprise) network with a virtually unlimited amount

Fig. 1: (a) Side and (b) top view of personal archipelago of transparency.



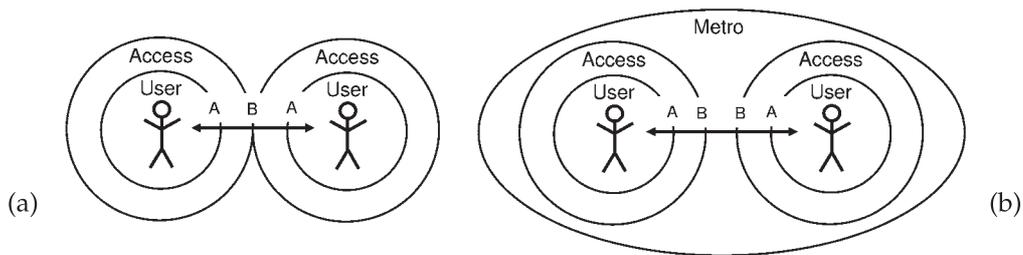


Fig. 2: (a) Local and (b) regional network PAT scenario.

of users [17]. In this paper, the wireless access network is considered to be a single tier. For example, the user can have a mobile phone to connect to a mobile base station (BS), which is connected to the access network. The BS represents node A in Fig. 1. A four-tiered infrastructure is also envisioned in future mobile and wireless access networks in which the optical infrastructure is considered to be a single tier [14].

A connection between two users can be visualized by considering the PATs of each user. As soon as an IoT along the data path is shared, it allows transparent communication in that domain. Fig. 2 shows a local and regional networking scenario using the PATs of two users. In the local networking PAT, scenario node B is shared between two access IoTs, while in the regional case, node B is transparently interconnected via the metro IoT. Obviously, the allowed distance between two users is much larger in the latter case.

III. Access IoT with mobility support

In this section, we discuss the requirements of an optical access IoT. We also present our design choices to realize such a network and show how this is related to the communication needs of a mobile user.

An optical access tier is required that supports user mobility in a heterogeneous landscape of wireless networks. This corresponds to the case where node A in Fig. 1 is an RAP or BS. The BS provides the wireless drop to the mobile user as well as the interconnection with the optical access. Through the BS, the fixed infrastructure network is directly related to the design and functionality of the wireless network. For example, the density of base stations is linked to the cell size, which is determined by the expected amount of subscribers, the type of mobile network, and the properties of the radio-frequency (RF) carrier.

The user mobility and the wireless network (or service) availability have an immediate impact on the resulting traffic streams in the optical domain. Consider the simple case of a long-reach/ low-bandwidth and a short-reach/high-bandwidth wireless network. Both networks are supported by the infrastructure and are available to the mobile subscriber. The communication needs of the subscriber may cause a horizontal, vertical, or even diagonal handover in the wireless domain, which represents a switch of the wireless channel between BSs, between networks, or between BSs and networks. As a result of a handover, the optical traffic has to be rerouted to the correct base station, the quality of service has to be adapted, or both. For an increasing number of subscribers and wireless networks, the optical access network needs to be able to provide guaranteed content delivery in an efficient, reconfigurable, secure, and, last but not least, cost-effective manner. The notion of cost and complexity reduction becomes more profound in the access network than in metro and core domains where capital and operational expenditure (CAPEX and OPEX) are naturally shared by many users.

A passive optical network reduces the amount of deployed fiber, which becomes efficient when the splitting ratio and/or the distance between the CO and the optical networking units (ONUs) increases [4]. The PON is particularly attractive in the access domain, where distances do not extend 5, 10, and 20 km for metropolitan, suburban, and rural areas [18]. OCDMA relies on optical communication via (an orthogonal) code as opposed to via a time slot or a wavelength. The code orthogonality allows the carrier to be asynchronously shared with other users on the network. OCDMA has many other attractive features such as efficient resource usage, resilience against eavesdropping and interference, and soft capacity degradation [19]. OCDMA on PON is an attractive and powerful combination because both are based on broadcast-and-select.

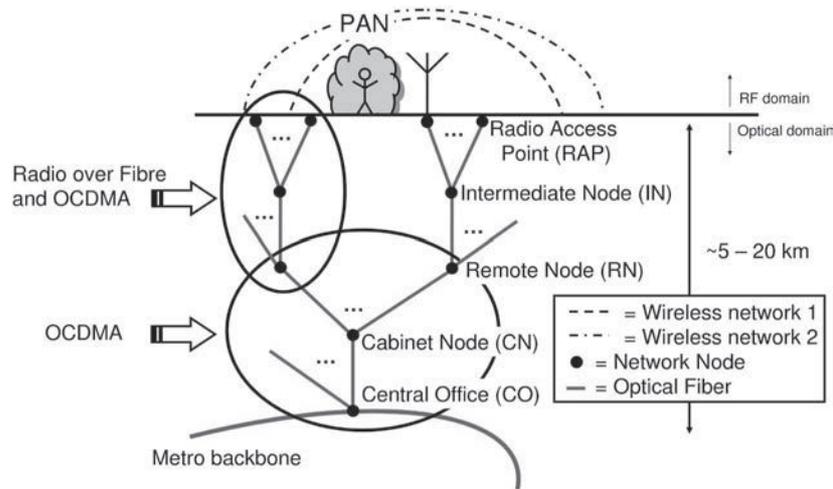


Fig. 3: Fiber-to-the-PAN network architecture.

Radio-over-fiber techniques enable one to perform the access control and signal processing of a wireless system at the central node and to deliver the radio signals transparently to simplified RAPs via optical fiber. Intelligence is centralized at the CO when using RoF on PON. The combination of PON, OCDMA, and RoF is a maximum sharing of CAPEX and OPEX.

The broadcast-and-select property of the PON facilitates horizontal handovers because the data are transmitted to all network nodes, i.e., no need to route data if RAPs are connected to the same PON. A vertical handover requires a network switch at the user side and/or at the RAP. Currently each network has its own infrastructure, such as base stations, and circuitry, in a network-aware device, which is not an efficient usage of resources at all. On the user side, however, software-defined radio (SDR) is an emerging technique. A device that supports SDR is a multistandard device and able to reconfigure a large part of its protocol stack to offer a high degree of flexibility [20]. Similar developments occur at the RAP side, e.g., a software-defined base station (SDBS) with similar capabilities as a device with SDR [21]. Both are envisioned capabilities of future wireless broadband networking [22]. Therefore, it is clear that future vertical handovers will occur between a single SDR terminal and a single SDBS.

In the case of the optical access layer, the reconfigurability at the SDBS is provided at the central node and all RF signals are delivered via a single optical fiber. The antenna site then merely exchanges data between an optical carrier and an RF carrier. From

this point of view, the user with its PAN might be able to receive the data directly from the fiber. Hence the total network from CO to RAP is denoted as fiber-to-the-PAN (FTTPAN). The RAP is then included in the PAN and represents node A in Fig. 1. The FTTPAN architecture is shown in Fig. 3 [23].

Two PONs are interconnected via a remote node (RN), namely, a "circuit switched" RoF/OCDMA PON and a "packet switched" OCDMA PON. This is similar to superPONs demonstrated in the literature in order to overcome the low splitting ratio of a single PON. In our case, we have placed intelligence in the intermediate node instead of just amplification. In a (sub)urban scenario, the RoF/OCDMA PON can be the fiber-in-the-home or fixed-wireless access and the OCDMA PON can be the fiber-to-the-home. The RN is then denoted as residential gateway (RG), which is placed at the user's premises [24]. Fig. 3 also shows an RAP that provides two wireless networks, as is described above in the handover example. The network-aware devices and the RAPs may use SDR and SDBS techniques in order to easily make a vertical handover between the two wireless networks.

IV. Personal networks

In this section, we present the concept and optical transparency requirements of personal networks. A user scenario is given that clearly shows several issues that are encountered when using today's technologies. It is shown that the optical IoT as presented in Section III mitigates many of these issues and adds functionality to the PN.

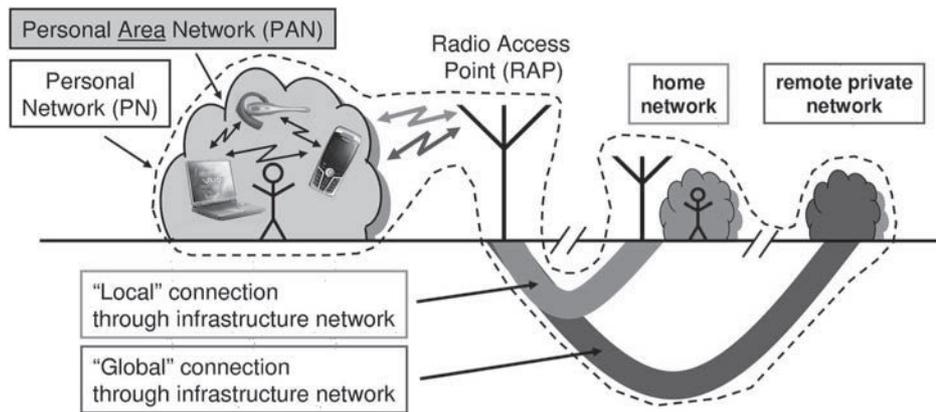


Fig. 4: A mobile user with its PAN and PN.

A. Concept

A PAN emerges when the network-aware devices carried by a user interconnect via a short-range wireless interface such as Bluetooth. Thus a PAN is a small, private, and literally mobile network. However, only resources located in the near presence can be included in the PAN because the wireless interface typically does not cover more than 10 m. Another important property of a PAN is that it is personalized, i.e., not all devices in the proximity of the user are included but only those that the user considers as his own, or has (temporarily) the right to access.

If a user would like to include remotely located resources or private networks (again, those that he considers as his own or has the right to use), access to a third-party network is required via, for example, medium-to long-range wireless interfaces such as wireless LAN (WLAN) or cellular networks. The local scope of a PAN is then extended to a global scope, but without modification of its personalized character. The network environment constituted by a PAN and connections to remote resources and networks is called a personal network [10]. The PAN and PN concepts are shown in Fig. 4. The figure shows a user with his PAN (gray). One or more devices in his PAN can also directly connect to the RAP with the aim to communicate to other personal devices not in the vicinity of the user, in the home network, or in other remote private networks. The devices that can directly connect to the RAP together are called the PAN gateway. Considering the connectivity to the home network (green), this IoT can be an optical fiber backbone in the home. Plastic optical fiber (POF) is preferred because it is very ductile and allows non-professional handling/installation, which can therefore be done by the user itself [25]. Its higher losses per unit length are not a restriction in the

home environment, and its lower bandwidth can be overcome by using advanced modulation techniques and signal processing [26]. To connect to other, remote private networks (blue), optical transparency has to be achieved using the POF backbone and the optical access network to the home. A residential gateway is then placed in between the in-home and the access network. If the RG is not transparent, it splits the access IoT of Fig. 1 in two parts. However, a transparent RG connects the POF home network backbone to the PON, using optical switching technology. If the remote private network is connected to the same PON, then optical transparency is guaranteed up to the remote network's ONU.

B. Optical Transparency Requirements in PnS

The following usage scenario is taken from [27] and will serve as a realistic but fairly complex example to extract more requirements with respect to optical transparency in PNs. An office worker is traveling home, in this case, a male person. While under way, he listens to MP3s, checks messages, has an international video call, programs a personal video recorder (PVR), etc. When arriving home, the front door opens automatically to let him in, the quality of the video call improves, the music session is taken over by the home sound system, and so on. When somebody rings the doorbell, the picture of the front door camera is displayed on a personal digital assistant (PDA) while he is away, or on the television screen while he is at home.

Reference [27] deduces requirements for the PAN and the rest of the PN with respect to service- and device discovery, connectivity, and mobility management. The PN-specific requirements concerning the latter two are the following.

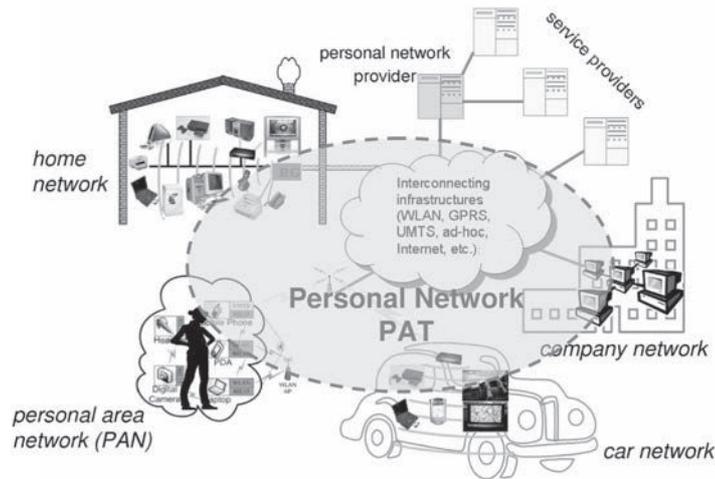


Fig. 5: Optical transparency domain in a personal network.

- 1) The PAN must allow devices in the PAN to connect directly to the home network when at home.
- 2) The PAN gateway must include the relevant interworking profiles for communication with public networks.
- 3) The connection between the PAN and the home network should be maintained, as well as the incoming sessions from outside the PN, when switching from one access network to another.

Then, [27] analyzes how an architecture containing existing technologies can fulfill the requirements. A heterogeneous PAN architecture is proposed, consisting of Bluetooth as well as HiperLAN/2. HiperLAN/2 has not had much market interest up to now. However, it is the only option if requirements 1) and 2) have to be met, considering the services described in the usage scenario, and assuming that the home network has a star configuration instead of a PON. The architecture also assumes that the end devices in the PAN and the home network support different higher layer protocols than in the public network, as is the case in the present day, and that the respective gateways are intelligent and perform all necessary protocol translations. For mobility management, a combination of MobileIP and session initiation protocol is suggested, adding even more complexity to the gateways.

Optical transparency can solve many of these issues. The main feature in the above usage scenario is the handover of the video call when arriving at home. The requirements in terms of delay are quite strict and cannot be met with current technologies, which have to perform a cumbersome

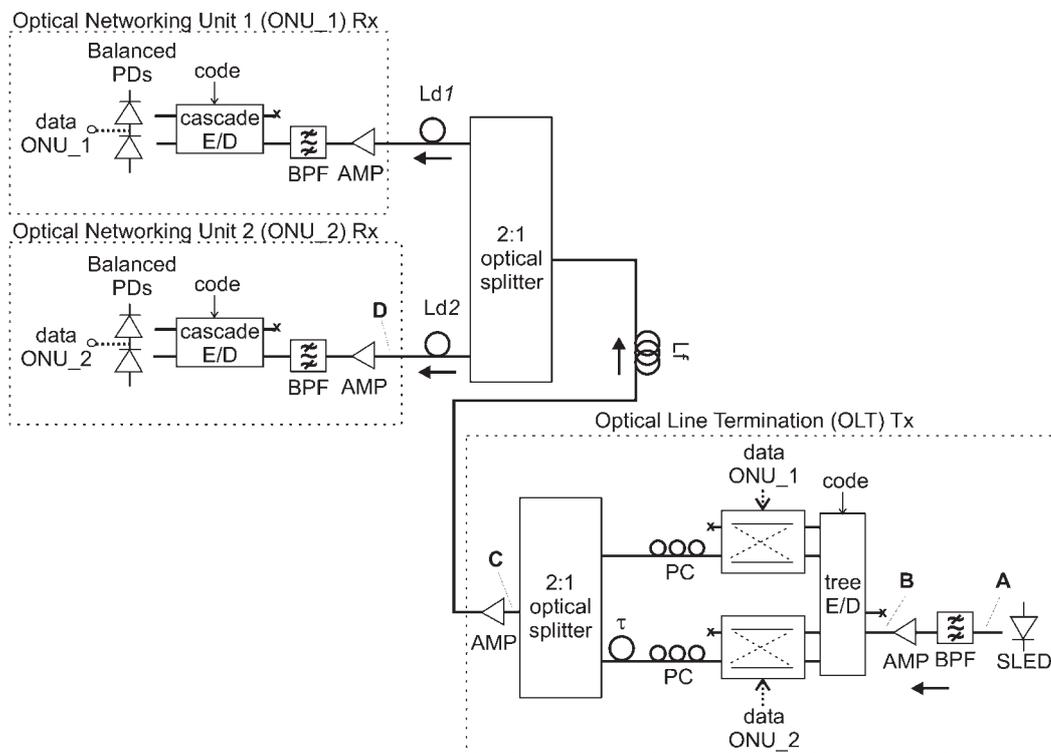
vertical handover between an operator's mobile network and a wireless home network connected to (another) operator's fixed network. As described in the previous chapter, the performance should greatly improve if the PN is a single PAT being a single broadcast-and-select domain, enabling horizontal handovers. Such a PAT is schematically given by the blue overlay in Fig. 5. Section III also concluded that such a broadcast-and-select domain requires central intelligence in the network for control and management of the PN. This is in line with the vision of the Freeband PNP2008 project [28], in which PNs are assumed to be managed by a personal network provider (PNP). The PNP is basically an omnipotent central server that controls the various nodes in the PN and presents an abstraction of the PN to third-party service providers. From a commercial and operational point of view, it represents a new business role that can typically be fulfilled by a telecommunications operator or an Internet service provider. The PNP is the service provider enabling the PN, offering third-party services to the PN, and providing an operational environment to manage user-, service-, content-, and network-related issues of the PN. For third-party service providers, the PNP might act as a one-stop shop for providing their services to the PN as a whole instead of to every single device separately. Theoretically speaking, this business role could also be performed by an expert user who knows how to run and maintain servers in one of his private network domains. However, end users cannot manage the physical layer properties of the public network, a skill needed to realize and control a PAT as depicted in Fig. 5.

A way to obtain optical transparency in the PN enabling the usage scenario is described below. Requirement 1) is fulfilled by applying the upcoming ultra-wide-band (UWB) technology¹ in the PAN as well as in the home network instead of the HyperLAN/2/BT combination, as previously suggested. Full coverage in the home can be achieved by installing a POF backbone, interconnecting at least one UWB node per room with each other and with the residential gateway. The RG is an optically transparent ONU connecting the home network to a PON access network. The UWB nodes can be relatively unintelligent RoF RAPs, and as such realizing FTTPAN. This turns the home network, or, better even, the whole neighborhood connected to the PON, into a single broadcast domain. Handovers are then merely a matter of switching on the device on which the user wants to receive the video call, because the PNP is receiving the video call from a third-party service provider and just broadcasts it in the PN. As long as the user moves within the coverage region of the UWB-PON system, also requirement 3) is met. Requirement 2) is met if the end devices involved support, for instance, the correct authentication mechanisms to ensure that the user tunes into the correct stream. If this puts too much strain on the end device, or if for some reason

the PAN needs to be authenticated as a whole, the PAN gateway should have more intelligence than a simple RAP. This would mean that the traffic in the IoT is terminated on the RAP node or on another device in the PAN serving as the gateway and proxying between IoT and PAN. If the user does not stay in reach of the PON, which is most likely the case in the usage scenario, optical transparency between PONs might be achieved over the metro network. Usually, however, the user is communicating via a cellular network while under way, and optical transparency can only be reached by interconnecting the mobile and fixed core networks, at last reaching the vision of optical mycelia as suggested in [14].

Optical transparency reached in the way as described above also eases the other services described in the usage scenario. Because the PN is now a single broadcast domain, MP3s and movies (PVR) in the PN are easily found and controlled with a multicast-based discovery protocol such as Universal Plug and Play. The automatic opening of the front door needs location dependence. A PN that is based on small wireless UWB cells delivers enough spatial resolution to conclude on the presence of the user at home when the correct RAP is detected

Fig. 6: Two-user downstream integrated SAE OCDMA PON [33].



1 WiMedia Alliance, <http://www.wimedia.org/>.

by the PAN. The same mechanism can be used to have the front door camera image projected on the correct device, which now is not more than a local decision to be made by the end device rather than the network performing a complete vertical hand-over.

V. Spectral amplitude OCDMA on PON

In this section, a general introduction is given on a cost-effective incoherent OCDMA technique and its use on PON. Various OCDMA techniques are studied today that can be differentiated by optical source (coherent or incoherent), coding domain (time, frequency, or time and frequency), en/decoder type (free space, fiber-based, or integrated), and electrical polarity (unipolar or polar). We consider incoherent spectral amplitude encoded OCDMA (SAE OCDMA) with periodic Mach-Zehnder interferometer (MZI)-based en/decoders (E/Ds). MZI-based E/Ds filter the broad spectral input and as such imprint their filter pattern being a spectral code (one period of the free spectral range). Tunable phase shifters enable one to modify the filter pattern to generate different, orthogonal codes [29]. At the receiver, an identical E/D is used to perform the decoding operation. Cascade [30] and tree [31], [32] E/Ds are placed at the ONU and optical line termination (OLT). A two-user downstream transmission scenario is shown in Fig. 6. Detailed information on integrated SAE OCDMA, the setup, and the upstream scenario can be found in [33].

The use of SAE OCDMA in the network has some specific unique advantages. Coding is performed at the bit rate which limits the receiver bandwidth, thereby offering additional cost savings. Incoherent broad spectral sources are used such as superluminescent light-emitting diodes (SLEDs), which are cost-effective compared with stabilized short-pulse single-wavelength sources. MZIs naturally produce two complementary fringe patterns. These are then used in spectral shift keying (SSK) by switching the optical signal from one input to the other [23]. SSK in combination with balanced detection results in polar electrical signalling for a 3 dB signal-to-noise (SNR) improvement. The recently demonstrated code-shift keying exploits the same principle but uses two different codes and is applied for a coherent short-pulse system [34]. The ONU and OLT are integratable with other optical functions on a chip and can be deployed in a

dynamic wavelength-division multiplexer (WDM) scheme.

VI. SAE OCDMA and OFM on PON

In this section, we analyze the integration of a radio-over-fiber system in the SAE OCDMA PON discussed in Section V. First, a specific RoF technique is introduced, namely, optical frequency multiplication. Then, the main issues in the integration of an OFM system and an SAE OCDMA system are analyzed from the transmitter and the receiver side. Finally, full system simulations provide insights in the performance of a hybrid SAE OCDMA OFM system on PON.

Many techniques to generate and deliver microwave signals via optical fiber have been studied in the literature such as optical heterodyning, direct transmission of RF signals, or harmonic generation. A promising technique is OFM because it makes use of a single laser source and low-frequency electronic circuitry to generate and deliver high-frequency radio signals to the RAPs [35]. Moreover, it has shown high tolerance to dispersion impairments in transmission over single-mode fiber (SMF) and multimode fiber (MMF). OFM is based on generating harmonics by frequency modulation to intensity modulation conversion through a periodic bandpass filter (BPF) such as an MZI or a polarization interferometer [36], [37]. The MZI-based E/Ds used in SAE OCDMA are also periodic BPFs and a potential sharing of this component by the OFM technique enables a compact solution to support both kinds of services simultaneously with the same architecture.

A. Transmitter

The main differences between the SAE OCDMA and OFM systems are the line width of the light source and the free spectral range (FSR) of the periodic BPF or MZI(-based) component used. In the OCDMA case shown in Fig. 6, the spectrum of the SLED is first filtered by a regular BPF with a 3 dB bandwidth equal to the FSR of the MZI-based E/Ds (typically several nanometers). In the OFM case, a distributed feedback (DFB) laser with a line width of a few megahertz and an MZI with an FSR on the order of tens of gigahertz are used. The ratio between the line width of the source and the FSR of the MZI(-based) component is given by the factor χ as follows:

$$\chi = \frac{\delta\nu}{FSR} \quad (1)$$

where $\delta\nu$ is the line width of the source in gigahertz and FSR is also in gigahertz. The factor χ has to be equal to one for SAE OCDMA in order to fully imprint the E/D's filter pattern in the optical spectrum. In OFM, χ is much smaller because the influence of the laser phase noise $\delta\omega (=2\pi \cdot \delta\nu)$ on the harmonic strength is only negligible if $\delta\nu \ll FSR/4$ [37]. Hence commercial DFB lasers with a typical line width of 1-100 MHz are used in an OFM system. Initially the two systems do not seem integratable, but further simulations have been done. Raising χ via $\delta\nu$ in an OFM system results in the generation of higher harmonics but with a decreasing SNR. This can be caused by the low extinction ratio obtained when phase-modulating a broad spectral slice with respect to the FSR. The harmonic strength also has a strong dependency on β , the FM index, which is determined by the optical broadening generated by the phase modulator and the sweep frequency. Thus the FSR of the MZI is inherently bounded by the optical broadening of the phase modulator. Typical values used at the moment are on the order of 50-60 GHz. It is clear that the components of both systems cannot be shared at the transmitter (central office); thus a separate OFM head-end is required.

B. Receiver

At the detection side, the SAE OCDMA system has an MZI-based E/D in front of balanced PDs (Fig. 6) instead of only a single PD at the OFM system. Mathematical analysis shows that harmonic strengths in OFM are influenced by adding an extra MZI with an FSR equally small as the MZI at the Tx-side. It is now even possible to cancel out even or odd

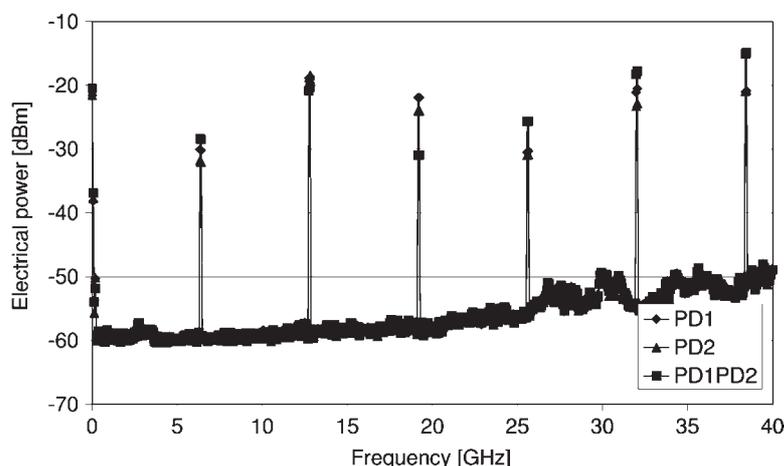
harmonics by choosing the sweep frequency and the FSR appropriately. The relative strengths of the harmonics can also be influenced by applying an extra phase shift in the additional MZI. However, the effect of adding the MZI-based E/D (with a large FSR) in the OFM system is not noticeable since the periodicity of the E/D is an order of magnitude larger than the MZI in OFM (see Section VI-A). As a consequence, only high RF broadcasting information can be transported via OFM, and user-specific information has to be transported via SAE OCDMA. In the latter case, the data can then be mixed with a selected RF carrier, generated by OFM. Higher constellation modulation formats are often used in RF networks. It has already been shown for optical code networks that these spectrally efficient modulation formats, for example, quadrature phase-shift keying or quadrature amplitude modulation, can be easily generated by either using four codes for each of the four phases [38] or two complementary codes (e.g., wavelength sliced spectra) for the I and Q channel [39].

We have also studied if the balanced detection would have a similar, positive effect on the SNR in case of OFM as it has in case of SAE OCDMA. A 40 GHz balanced detection unit of U²T was added to the setup as shown in [40]. Fig. 7 shows preliminary measurement results that indicate the SNR does improve by balanced detection but not at all higher harmonics.

C. Hybrid System

We have simulated the SAE OCDMA system as shown in Fig. 6 with an OFM system in VPI TransmissionMaker. The OFM signal was coupled into the link after the Tx of the OLT via a 3 dB coupler.

Fig. 7: Effect of balanced detection on harmonic strength in OFM system.



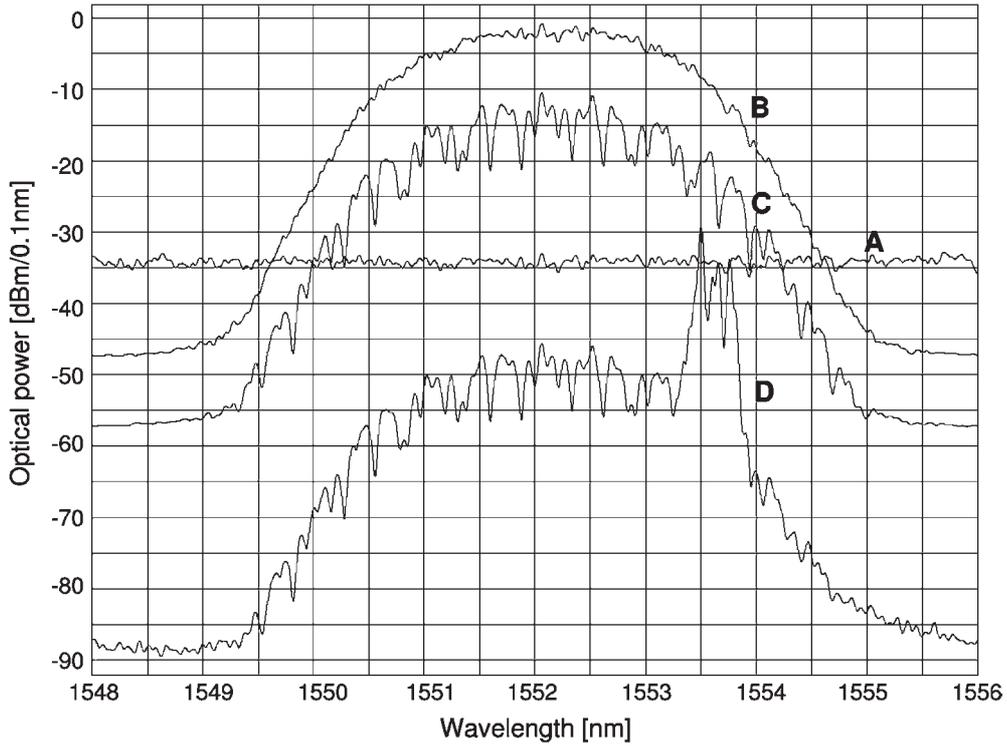


Fig. 8: Optical spectrum hybrid SAE OCDMA OFM system; (A) SLED, (B) SLED+BPF, (C) optical code, and (D) optical code+OFM.

Four-stage orthogonal cascade and tree E/Ds are constructed such that eight users can use the network [29]. The FSR in the SAE OCDMA system is only 256 GHz, which was a computing limitation. A single-user transmission is considered. The OFM system is simulated with the setup and settings shown in [40].

Three different scenarios are considered with respect to the position of the optical OFM signal in the optical code, namely, out-of-band, in-band, and in-band offset. As expected, the out-of-band placement of the optical OFM signal does not influence the performance of any of the two systems. The

in-band case, however, shows significant degradation of both systems. It is well known that OCDMA is robust against narrow-band interferers, but the 50 GHz optical OFM signal is just too dominant with respect to the only 256 GHz broad optical code. The optical spectra of the in-band offset scenario are shown in Fig. 8. The letters A through D show the position of the OSA as indicated in Fig. 6. Only fiber losses were simulated, which in total were 14 dB for the feeder and distribution fiber. The position of the OFM signal has not been optimized yet. The higher harmonics and the received bit sequence (inset) are shown in Fig. 9.

Fig. 9: Received electrical signal hybrid SAE OCDMA OFM system (inset: SAE OCDMA bit stream).

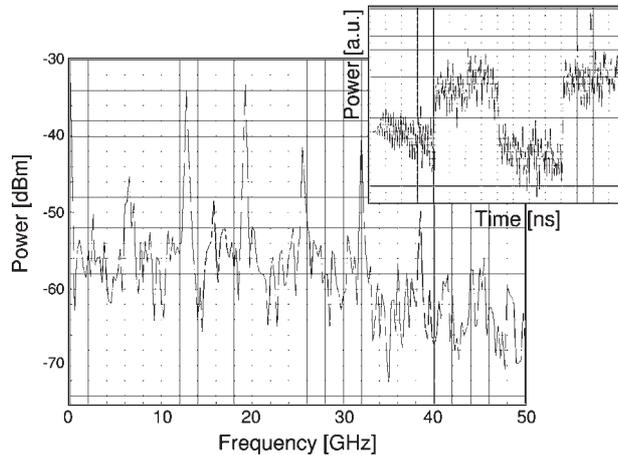


Fig. 9 shows the proof-of-concept of a hybrid SAE OCDMA OFM PON. The large signal fluctuations observed in the inset are caused by speckle noise, which is a well-known phenomena when using amplified spontaneous emission sources. Possible countermeasures have been proposed in [33], such as to drive the sources in the gain-saturation regime, to enlarge the FSR of the MZI E/D, and to include a limiting electrical amplifier with thresholding.

VII. Contention resolution in OCDMA PON

In this section, we introduce a novel code-wavelength distribution to enable transparent peer-to-peer communication between different ONUs in different PONs. Contention resolution is achieved via a code-sense collision-detection medium access control and packet switching. Both functions are implemented in the optical domain to preserve the network transparency.

We consider the case of an OCDMA WDM PON in which each ONU is identified by an optical orthogonal code on a separate up-and downstream wavelength. The central office is not limited to only having a single PON connected (as in [18]), and communication is not only bound between the CO and an ONU. The CO may have a subnet of PONs in which ONUs are allowed to freely communicate with each other inside (intra) a PON and in between (inter) PONs. A requirement in this case is that the optical transparency should be preserved. In other words, the transmitted data packets should always remain in the optical domain and (preferably) no wavelength conversion should be applied. If the up-and downstream wavelengths are fixed, for example, because of standardization, a labeling technique such as generalized multiprotocol label switching (GMPLS) can be used to route and multiplex the data packets. Another approach is presented here by using especially allocated "peer-to-peer" wavelengths next to the up-and downstream wavelengths and to use the code of the addressee. Each PON in the subnet will then have a unique wavelength on which data intended for and sent by other ONUs can be sent and received. The broadcast-and-select properties of PON and OCDMA ensure that the data are received correctly. Additionally, CO-ONU and ONU-ONU communication is then separated in the frequency domain. The optical code is then used as modulation format, as multiple access

mechanism, and as label recognition. A similar use of the optical code is presented in [41], but in that work the application is subwavelength packet switching in core OC-GMPLS networks. Data packets may collide at one of the aggregation points when multiple ONUs simultaneously transmit to a similar destination (same wavelength and same code). This is the case both for intra-and inter-PON traffic. Two aggregation points are identified: the passive splitter for ONUs located in the same PON or the central office for ONUs located in different PONs in the CO's subnet. We propose a combination of optical collision detection and optical packet switching for contention resolution at these two nodes.

A. Layer 2: Optical Code-Sense Collision Detection

A medium access control is required to avoid collisions at the passive splitter. Previous work on ethernet MAC protocols for a PON focused on optical carrier-sense [42], [43]. For a code-division network, this obviously does not result in correct detection of collisions. To mitigate this issue, an MAC protocol based on optical code-sense is required. We propose optical code-sense multiple access/collision detection (OCSMA/CD) to upgrade an OCDMA PON [44]. Optical code-sensing has been analyzed for IP routing in a fiber Bragg grating (FBG)-based SAE OCDMA star network by [45]. In [44], the passive splitter requires a minor upgrade in order to have directional coupling to all-but-own-fiber such that OCSMA/CD works on PON. The code-sensing unit is easily implemented at the transmitter because of the reciprocity of the OCDMA en/decoder. However, this OCSMA/CD MAC has two important limitations to consider.

The first limitation is that any transmission by an ONU has to be received by all other ONUs in the PON before it stops transmitting data. The minimum round-trip time (RTT) is determined by the minimum ethernet packet length of 72 bytes. The simple formula in (2) calculates the fiber length L as a function of t_{RTT} as follows:

$$2L = \frac{c \cdot t_{RTT}}{\eta_{eff}} \Rightarrow B \cdot L = \frac{c \cdot \ell_p}{2 \cdot \eta_{eff}} \quad (2)$$

where c is the speed of light, η_{eff} is the effective refractive index of a standard single-mode fiber (SSMF), and t_{RTT} is equal to the transmission time ℓ_p/B with ℓ_p the packet length in bits and B the bit

rate. Equation (2) shows that OCSMA/CD limits the bit rate on a PON for a given length of the distribution fiber or vice versa. For example, when each user employs a gigabit ethernet (GbE) connection (1.25 Gbps), the transmission of the smallest packet via fiber corresponds with $L \approx 50$ m for the distribution fiber. This limits the deployment of the PON either to a very short-range GbE small office/home office network or to a more distributed networking environment with speeds up to several hundred megabits per second. Bit stuffing may also be applied in order to increase the minimum packet length.

A bit rate of several hundred megabits per second may be sufficient if we consider the traffic streams in an FTTPAN architecture. They are dominated by the communication needs of the mobile subscriber. As mentioned in Section III, high bandwidths in wireless networks require high RF carriers and result in small network cells. Many RAPs or ONUs are needed if a particular area is to be fully covered. The geographical coverage of FTTPAN is restricted because of the short reach of such wireless networks. The splitting factor and transmission distance of truly passive optical networks is also limited. As a result, the probability that a source and destination reside in the range of a single FTTPAN architecture becomes small. If the source and destination do reside in the same subnet of the central office, a peer-to-peer connection will be established. In the case of FTTPAN, we assume that the majority of the traffic requires a connection between CO and ONU because the destination is located outside its range [46]. Thus GbE speeds or higher are not yet required for peer-to-peer communication in FTTPAN employing OCSMA/CD.

The second limitation of the solution in [44] is that OCSMA/CD is difficult to implement for intra-PON peer-to-peer communication. In that case, the ONU tunes to the wavelength on which the downstream data are being transmitted. If no data are sent to the addressee at that instant, the ONU first sends the data to the central office. The CO will then immediately route the data downstream on the shared network. If the transmitter is still transmitting, it then receives part of its own transmitted data and the OCSMA/CD MAC detects collision. This is related to the maximum ethernet packet length of 1526 bytes, which, following (2), corresponds with $L \approx 1$ km for the distribution and feeder fiber. Most deployed PONs have longer transmis-

sion distances so in that case, this would not impose a problem. If data are sent to the addressee at that particular moment, the OCSMA/CD shuts the transmission down because it detects collisions. The latter scenario imposes a serious problem. The consequence is to have intra-PON traffic in a different wavelength band via wavelength conversion at the CO, not to allow intra-PON peer-to-peer communication on the network, or to have space-division multiplexing (SDM) of the up-and downstream channels.

In this paper, we consider the optical transparent solution of SDM. As a result, we have an OCSMA/CD PON next to an OCDMA PON to clearly separate the up-and downstream channels of the peer-to-peer communication. This hybrid solution is shown in Fig. 10. The (upper) OCSMA/CD PON only carries the upstream peer-to-peer channels to mitigate both drawbacks of OCSMA/CD because the bit rates on the (lower) OCDMA PON are not limited. The downstream peer-to-peer traffic is then routed to the OCDMA PON. Such scenario also allows simultaneous transmission of intra-and inter-PON traffic. The situation in Fig. 10 can be considered as a migration step towards using a single PON architecture in FTTPAN. Fig. 10 shows the four different kinds of traffic streams. The corresponding code/wavelength combinations are shown in Table I, with λ_{up} and λ_{down} as the up-and downstream wavelengths, λ_{in} and λ_{out} as the wavelengths for intra-and inter-PON peer-to-peer communication, and c_s and c_d as the source and destination code.

B. Layer 3: Optical Code Packet Switching

The upstream traffic arriving at the central office has an asynchronous nature because of the use of optical codes on the network. Multiple packets to multiple destinations may arrive per wavelength because of the extra dimension offered by the orthogonal optical codes. When two ONUs are located in different PONs and send data packets to a similar destination, the packets will have the same optical address (similar code plus wavelength). A collision is at stake when both packets

Table I: Code/wavelength combinations

	OCDMA PON	OCSMA/CD PON
upstream	$(\lambda_{\text{up}}, c_s)$	$(\lambda_{\text{in}}, c_d), (\lambda_{\text{out}}, c_d)$
downstream	$(\lambda_{\text{down}}, c_s), (\lambda_{\text{in}}, c_s)$	-

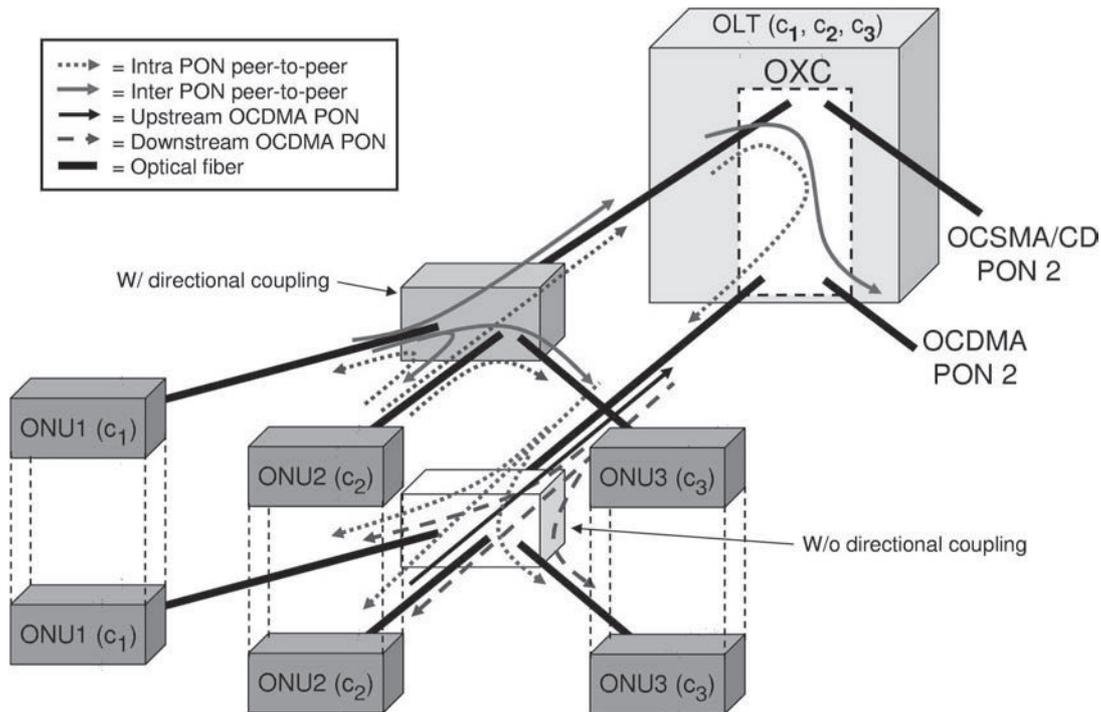


Fig 10: Hybrid OCDMA PON-OCSMA/CD PON architecture.

arrive in the same time window. Hence a code-based packet switch is required for contention resolution at the central office. A two input by two output (2×2) switch node is shown in Fig. 11, which is placed in the OLT of Fig. 10. The number of input and output ports can be easily increased. Fig. 11 does not show the handling of the regular OCDMA traffic between the CO and ONUs since this is a standard operation. A simple transmission scenario is shown. Three packets arrive from ONUs in OCSMA/CD PON 1 at $t = t_0$ and $t = t_1$ ($c_{1,1}$ indicates code 1 sent from PON 1). Only one packet arrives from an ONU in OCSMA/CD PON 2 at $t = t_1$. The latter packet has a similar optical code and wavelength combination as one of the former three, but it arrived a little later. Therefore, the data packet from OCSMA/CD PON 2 will be buffered. The buffer time depends on the total propagation time of the upper packet through the switch and on the length of the packet. All packets are then correctly switched from OCSMA/CD PON 1 and 2 to OCDMA PON 1 and 2. The principle of operation of the switch is described in the following paragraphs.

At the input port, the wavelengths are separated by a wavelength demultiplexer (λ DEMUX), after which an optical code (OC) demultiplexer unravels the optical packet stream into separate packets per output port. The optical code demultiplexing operation

can be easily done via OEO packet regeneration but a fully optical solution is desired to preserve the optical transparency. A similar component is used in the OC-GMPLS subwavelength core switch of [41] because also in that case the optical code is applied to the whole packet. The authors refer to this technique as *implicit* optical code labelling (ImOCL). The OC DEMUX is not required when optical codes are used as header in *explicit* optical code labelling (ExOCL), for example, in hop-by-hop label-switching networks [47]-[49], or when codes are used as routing dimension [50].

The packets are synchronized after the OC DEMUX, and part of the optical power is led through a control and code processing unit. The synchronization can be done, for example, by switchable delay lines [51]. The code processor checks the correlation properties with all available optical codes per wavelength, which can be cost-efficiently done by a parallel decoder [32], [49]. Based on the information from the code processor, it is decided if an optical packet has to be buffered or not. The routing information may already be retrieved at the output of the OC demultiplexer to simplify the architecture. The switch matrix switches optical packets either to the output port or an optical buffer. At the moment most optical switching technologies are a combination between optical techno-

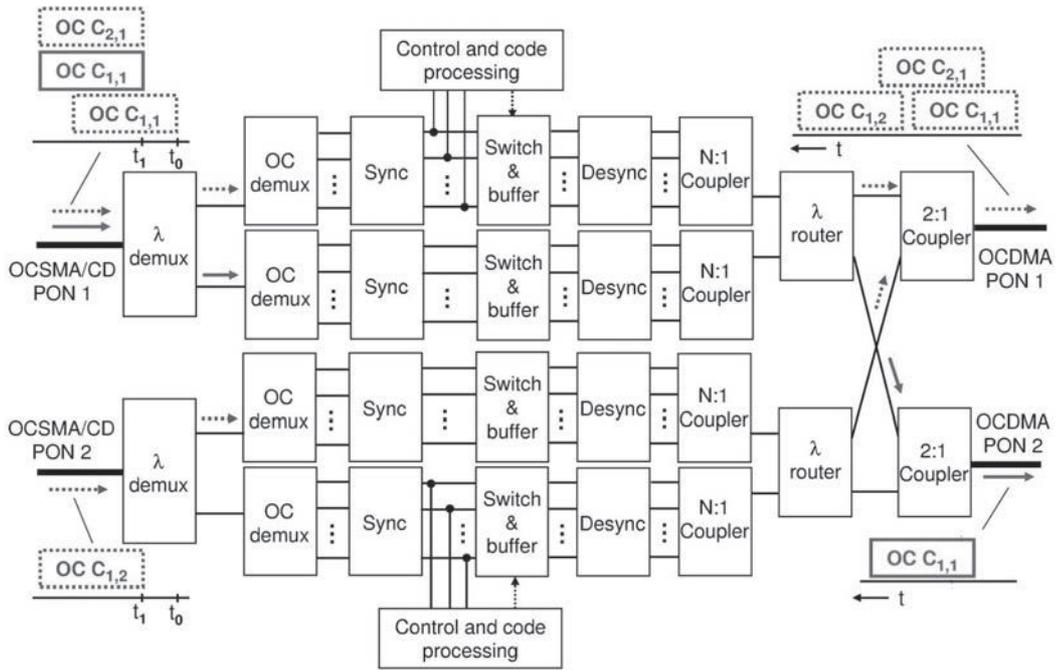


Fig 11; Optical code packet switch between OCDMA-OCSSMA/CD PONs.

logy and electronics [52]; thus an electrical control signal is required from the control and code processing unit in Fig. 11. However, an all-optical approach with optical control signals has been demonstrated and shown feasible for contention resolution by [53]. A recirculating configuration of fiber delay lines (FDLs) is envisioned as a buffer unit as it reduces the amount of fiber needed and provides more flexibility because of the shorter fiber lengths used. The optical packets can be also accessed upon each recirculation through the switch fabric. However, the recirculating buffers introduce additional losses, noise accumulation, and crosstalk [54].

After the switch matrix, the packets are desynchronized because synchronous multiplexing of OCs (or chip synchronous traffic) represents the worst case scenario in the case of a timedomain OCDMA network [50]. Hence the desynchronization should have relative delay values that are not a multiple of the bit time. A passive splitter/combiner is used to multiplex the packets to the output fiber. A wavelength (λ) router has been added in order to have full reconfigurability of the switch and of the WDM layout used in the network. This can be implemented, for example, by a reconfigurable optical add-drop multiplexer [55] or a wavelength-selective switch [56]. The final component is a simple optical splitter/combiner to multiplex the different downstream channels to the OCDMA

PON. Obviously, the optical signals need to be amplified at various locations to compensate the losses of the switch. The wavelength demultiplexer and router can be replaced by an arrayed waveguide grating (AWG) if full flexibility is not required. The optical cross-connect does not contain any label swapping unit because FTTPAN is a single-hop wavelength routing network and the source sends its data with the address of the destination.

VIII. CONCLUSION

The future communication needs of mobile subscribers are reflected in personal networks for global connectivity to personalized resources. An optical transparent access layer mitigates many issues currently encountered regarding connectivity and mobility management in PNs. In this paper, we focused on two transmission domains: the home and the (traditional) access network. The application of PON, OCDMA, and RoF techniques in home networks decreases the need for distributed control and management, and therefore intelligent and expensive residential gateways. It also paves the way for, for instance, ultra-wide-band to enable cost-effective, truly broadband mobility in the home network and any other cluster network in the PN. This is the first time that such lower layer converged optical-wireless architectures are considered and analyzed for their usefulness in PNs. In the access network, we propose

optical peer-to-peer networking to further increase the transparency between network nodes and to support future Internet services. A hybrid solution of a code-sense medium access control protocol and an optical code packet switch, implemented in the same optical physical layer, has been shown for the first time for contention resolution in a peer-to-peer enabled OCDMA/WDM network.

Acknowledgment

The authors would like to acknowledge J. Herrera Llorente for valuable comments.

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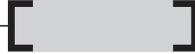
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A.H. Ghamarian

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Gedrag van radiogolven in mobiele netwerken in beeld brengen

dr.ir. Maurice Kwakkernaat
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De toename van het gebruik van mobiel internet en telefonie legt een zware last op de capaciteit en betrouwbaarheid van mobiele netwerken. De meeste problemen doen zich vooral voor in dichtbebouwde stedelijke omgevingen en laat dit nu juist de plek zijn met de meeste mobiele gebruikers. Het verhogen van de betrouwbaarheid en de capaciteit staat bij mobiele operators dan ook hoog op de agenda. Het nauwkeurig voorspellen van het gedrag van radiogolven in dit soort situaties is nog

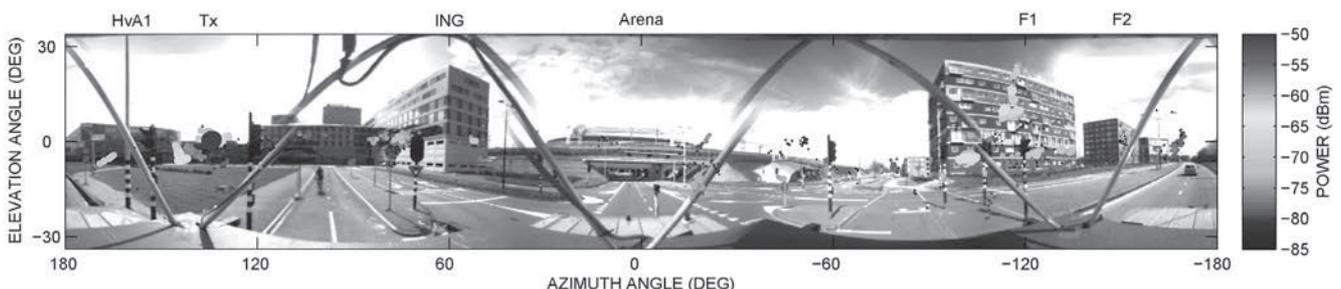
steeds erg lastig en vereist meer kennis over het echte radiogolf gedrag. De TU/e ontwikkelde een uniek meetinstrument dat de knelpunten in mobiele netwerken in beeld kan brengen. Het meetsysteem is onlangs in samenwerking met TNO ingezet in Amsterdam en Rotterdam om knelpunten in mobiele netwerken en de oorzaken hiervan in beeld te brengen.

In een van de analyses draait het om het gebied rondom de Amsterdam Arena. Er staan daar twee UMTS zendmasten. Eén van de masten zou dekking moeten geven in een bepaald gebied, maar dat bleek niet voldoende het geval en daarbovenop bleek de straling van de andere mast het signaal te storen op plekken waar dat volgens de voorspellingen eigenlijk niet zou moeten kunnen. Met het meetsysteem dat geïnstalleerd is in en op een bestelbus, zie figuur 1, is in kaart gebracht hoe dat komt. De radiostraling blijkt door gebouwen en andere objecten, zoals bomen en lantaarnpalen, te worden afgebogen en weerkaatst. Door gebruik te maken van omni-directionele videobeelden wordt met gekleurde vlekken exact getoond hoe dat gebeurt, zoals in figuur 2. Er wordt namelijk bepaald vanuit welke richting en met welke tijdvertraging de speciale antenne op het dak van het busje de radiostraling ontvangt.

Figuur 1: Meetsysteem voor het in beeld brengen van radiogolven.



Figuur 2: Omni-directionele foto met daarin de ontvangen signalen in kleur weergegeven.



Meer datasnelheid, meer betrouwbaarheid

De problemen zoals die bij de ArenA zijn niet zeldzaam en blijven alleen maar toenemen door de steeds hogere eisen die we stellen aan mobiele netwerken voor toepassingen zoals mobiel internet. Er is een sterke trend van altijd en overal toegang hebben tot het internet. Dat stelt hoge eisen aan het mobiele netwerk.

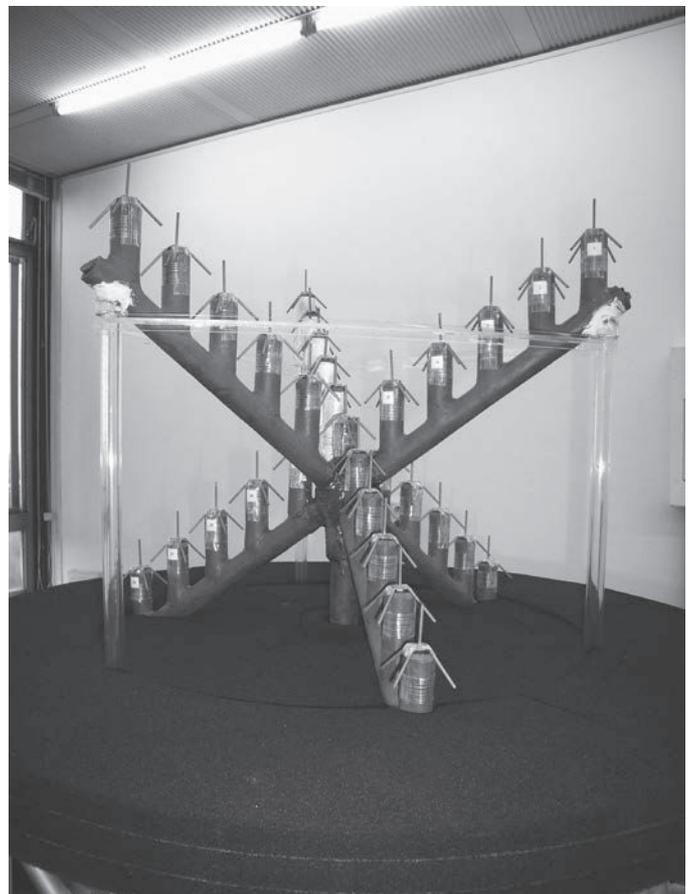
Maar in stedelijke omgevingen komen er door obstakels in de omgeving talloze radio-echo's vanuit verschillende richtingen aan bij de ontvanger. Een signaal dat de ontvanger via verschillende paden bereikt veroorzaakt fading en kan storing veroorzaken. De reflecties kunnen echter ook bijdragen tot het verbeteren van de betrouwbaarheid, kwaliteit of het verhogen van de data snelheid. Hierbij is het wel belangrijk dat er voldoende kennis van de omgevingseffecten beschikbaar is bij het ontwerpen of uitrollen van een mobiel netwerk. Vooral het gebruik van zogenaamde slimme antennes of MIMO kan hieraan bijdragen. Dit soort multi-antenne systemen zijn in staat om in specifieke richtingen hun energie te bundelen. Op deze manier kunnen de eerder ongewenste radio-echo's gebruikt worden voor het verhogen van de kwaliteit of de datasnelheid. Nauwkeurige kennis over de richting van de radio-echo's is hierbij van groot belang. Ook bij het uitrollen en onderhouden van mobiele netwerken is het noodzakelijk om een goede voorspelling te kunnen doen over de manier waarop radiogolven zich voortplanten. Hierbij moet er gezorgd worden dat er voldoende dekking is en zo min mogelijk storing. Om meer kennis hierover te verkrijgen zijn geavanceerde metingen noodzakelijk.

Uniek meetsysteem

Het meetsysteem is afgelopen jaar samen met TNO gebruikt voor de hierboven beschreven analyse. Het bestaat uit twee hoofdbestanddelen: een antenne en een videocamera, die beide op het dak van een busje zijn gemonteerd. De antenne, getoond in Figuur 3, is een uitgebalanceerd ontwerp waarover lang is nagedacht. Hij is opgebouwd uit maar liefst 31 kleine antennes, verdeeld over drie elkaar kruisende rijen, op zo'n manier dat nauwkeurig (binnen vijf graden) kan worden vastgesteld uit welke richting de opgevangen straling afkomstig is.

De antennes worden om beurten uitgelezen, in een zich herhalende sequentie die in totaal minder dan een milliseconde duurt. Snel uitlezen is nodig, omdat het busje tijdens de meetsessie gewoon aan het verkeer deelneemt, en dus niet elke meter kan stoppen om even rustig data binnen te halen. Met dit systeem kunnen we meten terwijl het busje met maximaal vijftig kilometer per uur rondrijdt. Om de exacte positie en oriëntatie van de antenne bij te houden, is het busje ook voorzien van een geavanceerd GPS-systeem met aanvullend kompas, hoogtemeter en apparaatjes die de versnelling en draaibewegingen van het voertuig in kaart brengen. Al deze instrumenten zijn nodig om het standaard GPS-signaal aan te vullen, voornamelijk als de ontvangst wordt verstoord door omringende gebouwen. Behalve de radioantenne bevat het busje ook een zogeheten omni-directionele videocamera, die de omgeving rondom de antenne over een bereik van 360 graden in beeld brengt. Deze beelden worden over radiometingen gelegd, waardoor in een oogopslag zichtbaar is wat de bronnen van ongewenste radioreflecties zijn, zoals in Figuur 2.

Figuur 3: Antennestelsel bestaande uit 31 antenne-elementen in een 3D gedraaid kruis.



Het Klokhuis

Het meetsysteem is niet alleen prima geschikt voor nauwkeurige metingen, maar presenteert de resultaten vooral ook op een inzichtelijke en aansprekende manier. Om deze reden is het ook gebruikt tijdens opnames voor een uitzending van Het Klokhuis over het onderwerp "De Mobiele Telefoon". Deze opnames zijn uitgezonden op woensdag 10 februari 2010 om 18:25 op Nederland 3.

Maurice Kwakkernaat is momenteel werkzaam via TMC Electronics als Consultant en Researcher op het gebied van mobiele communicatie, radar systemen en sensor netwerken.

