Current Research in the Area of Photonic Network Technologies

Slavisa Aleksic
Vienna University of Technology,
Institute of Broadband Communications
Favoritenstrasse 9/388,
A-1040 Vienna, Austria

Abstract: Photonic networks are probably the most appropriate solution to meet growing bandwidth requirements in the present as well as in the future Internet. The very high bandwidth of optical fibers can be exploited to some extent by using advanced modulation formats and by multiplexing the data either in the wavelength, in the time, or in the code domain. The development of key technologies for ultra high-capacity optical transmission has made possible transmission experiments with very high bit rates and a large number of wavelength channels. Today we speak about transmission capacities of above 10 Tbit/s (10^{12} bits per second) over a single optical fiber. New telecommunications applications such as multimedia, telemedicine, high-speed access to large databases, clustering, and grid computing require a dynamic, high-capacity photonic network with the capability to carry heterogeneous network traffic. In order to be able to satisfy these requirements, high-performance network nodes that are capable to process many parallel high-speed signals directly in the optical domain have to be developed. Such all-optical network nodes have to provide a dynamic access at high bit rates and to ensure efficient bandwidth utilization in order to meet the high requirements and to satisfy the enormous demand on bandwidth in the Next-Generation Internet (NGI). This paper gives an overview on new technologies and research directions in Europe in the field of photonic networks. Moreover, two large European research projects are presented. Current and future trends, perspectives, and the main steps towards digital optical Internet are discussed.
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Keywords: Photonic networks, optical transmission, optical signal processing, European research, Next Generation Internet

Sažetak: Fotoničke mreže su vjerojatno najprikladnije rješenje za zadovoljavanje stalno rastuće potrebe za visokim kapacitetom prijenosa podataka kako u sadašnjem tako i u budućem Internetu. Veoma veliki kapacitet prijenosa podataka preko optickih vlakana može se već danas u velikoj mjeri iskoristavati do odredjenih granica uz primjenjivanje naprednih modulacijskih formata i multipleksiranja u vremenskom domenu, u frekventnom domenu ili u domenu kodova. Razvoj ključnih tehnologija za izuzetno brzi prijenos podataka kroz opticka vlakna omogućio je provođenje eksperimenata jako velikog kapaciteta prijenosa uz korištenje velikog broja kanala i sa velikim brzinama prijenosa u svakom od kanala. U današnje vrijeme, već možemo govoriti o mogućnosti prijenosa više od 10 Tbit/s (10^{12} informacijskih jedinica u jednoj sekundi) preko samo jednog optičkog vlakna. Nove telekomunikacijske aplikacije kao što su multimedija, telemedicina, brzi pristup velikim bazama podataka, clustering kao i grid computing zahtjevaju jednu dinamičku mrežnu infrastrukturu visokog kapaciteta sa sposobnošću prenošenja heterogenog mrežnog prometa. Da bi se to uspjelo dostići moraju se prvo razviti mrežni čvorovi izvanrednih osobina koji mogu istovremeno obrađivati veliki broj brzih signala direktno na optičkoj razini. Takvi potpuno optički, mrežni čvorovi moraju omogućiti dinamički pristup pri visokim brzinama prijenosa podataka, kako bi se osiguralo eficijentno korištenje velikog kapaciteta optičkih prijenosnih sistema i na taj način udovoljilo ogromnim zahtjevima budućih generacija Interneta. U ovom clanku moze se naci pregled novih tehnologija i istraživačkih pravaca u Evropi u oblasti fotoničkih mreža. Osim toga, predstavljena su dva velika Evropska projekta. Sadašnji i budući trendovi, perspektive i najbitniji koraci u pravcu digitalnog optičkog Interneta su takođe razmatrani.

Ključne riječi: Fotoničke mreže, optički prijenos podataka, optička obrada signala, istraživanje u Evropi, nova generacija Interneta

1. INTRODUCTION

The fast growth of aggregated Internet traffic and development of new telecommunications applications such as supercomputer interconnections, interactive TV, multimedia, grid computing, storage area networks, as well as telemedicine applications are subject to a tremendous bandwidth demand. This demand on more and more bandwidth can be satisfied by employing optical fibers, and thus, photonic networks.

Photonic networks that allow signals to remain in the optical domain from a source to a destination node, thereby providing improved capacity, transparency, and efficiency, are referred to as all-optical networks. The efficiency of the data transmission can be further improved by equipping the network nodes with very fast photonic switching and processing modules. Then we can perform switching on a packet-by-packet level that is referred to as all-optical packet switching. Thus, all-optical packet-switched networks could be used to satisfy the enormous demand on bandwidth in the Next-Generation Internet (NGI).

Currently, most research efforts in photonic networks concentrate on three primary techniques for multiplexing data onto a single fiber: wavelength-division multiplexing (WDM), optical time-division multiplexing (OTDM) and optical code-division multiplexing (OCDM). The major part of that research is devoted to WDM systems. An important reason lies in the fact that the basic technologies used in WDM networks are to a large extent commercially available (e.g. optical filters, WDM demultiplexers, sources with narrow linewidth, etc.). On the other hand, OCDM has been receiving considerable attention in recent years. However, the implementations of the OCDM technology are yet restricted to applications in local area networks (LANs) using a star topology.

OTDM technology can be used to maximize the utilization of the optical fiber by circumventing the electronic bottleneck, thereby providing high-speed access to the optical fiber. The access to the high-speed optical TDM network can be realized by using one of the two main multiplexing techniques: bit-interleaved OTDM or packet-interleaved OTDM. Very recently, point-to-point transmission of a differential phase shift keying (DPSK) OTDM signal at 2.56 Tbit/s over 160 km of dispersion-managed fiber has been reported [6]. Several high bit-rate OTDM signals can be transmitted in parallel on several wavelength channels using a single fiber. Thus, the very high capacity of a single fiber can be exploited effectively by concurrently using both OTDM and WDM techniques. There are experiments carried out with more than 10 Tbit/s transmission capacities over a single fiber by using OTDM, dense WDM, OCDM, and advanced modulation formats (see Figure 1).

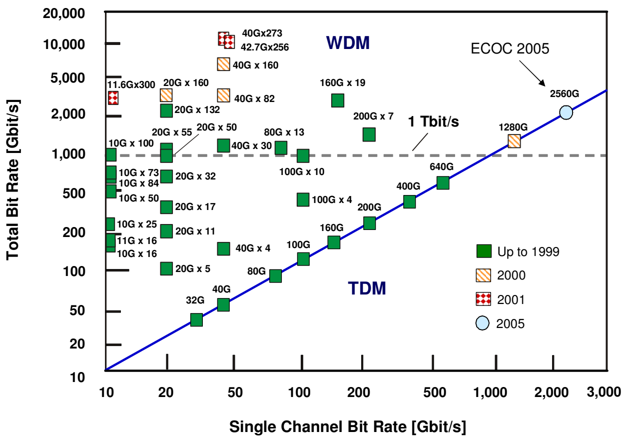

Figure 1: Optical transmission experiments, Sources: LEOS Newsletter 10/99, OFC 2000, ECOC 2000, OFC 2001, ECOC 2005 (TDM: Time-Division Multiplexing, WDM: Wavelength-Division Multiplexing).

2. EUROPEAN RESEARCH ON PHOTONIC NETWORKS

The European research in the area of photonic networks is funded either by national or international science funds or by a private institution or a company. The most important funding source in Europe is the Sixth Framework Program (FP6) of the European Union [1]. Within the area of the Information Society Technologies (IST), there are many projects running at the moment in the area of the communication technologies and in particular on optical technologies and networks [2]. There is also a number of initiatives and actions within the Information and Communication Technology (ICT) sector, which are established and performed on the basis of the Lisbon goals and strategy and renewed in the so called "Vienna Process" that should help to forge a common European strategy towards ICT research and to align European, national, regional, and private research activities.

In the following, some of IST projects related to photonic networks are listed. Some of them are Integrated Projects (IPs) other are Networks of Excellence (NoE), specific targeted research projects (STREP) or coordination actions.

1. Low-cost 1.3 µm sources for FAST ACCESS technologies (FAST ACCESS)
   - STREP with 4 partners
   - The aim of this project is to develop low-cost, 1.3 µm dilute nitride laser sources for use as directly-modulated transmitters in access applications.
2. Functional Photonic Crystal Devices for Metropolitan Optical Networks (FUNFOX)
   - STREP with 8 partners
   - The aim is to develop and use photonic crystals to miniaturize and improve semiconductor optoelectronic devices needed in metropolitan core and access networks.
3. All-optical label swapping employing optical logic gates in network nodes (LASAGNE)
   - STREP with 9 partners
   - This project aims at studying, proposing, and validating the use of all-optical logic gates and optical flip-flops based on commercially available technologies to implement the required functionalities at the metro network nodes in all-optical label-switched networks.
4. European Network of Excellence on Photonic Integrated Components and Circuits (EPIXNET)
   - NoE with 32 partners
   - The project addresses integrated optical, opto-electronic, and photonic functional components and focuses on five major themes: photonic integration technology, nanophotonics, advanced semiconductor materials, ultra-fast light sources and ultra-fast signal processing.
5. Optical Networks: Towards Bandwidth Manageability and Cost Efficiency (E-PHOTON/ONE+)
   - NoE with 40 partners

- This Network of Excellence aims at integrating and focusing the rich know-how available in Europe on optical communications and networks, both in universities and in research centers of major telecom manufacturers and operators.

6. Advanced Technology for Holographic Storage (ATHOS)
   - STREP with 7 partners
   - The objective of this project is to develop the technological basis for a new-generation, high-capacity, compact and cost-effective holographic data storage system. Specific key components such as laser sources, optical, and opto-electronic components, electronics, and media substrates will be developed.
7. Broadband in Europe for All: a Multi-Disciplinary Approach (BREAD)
   - Coordination action
   - This coordination action aims at developing a multi-disciplinary approach for the realization of the 'broadband for all' concept within Europe.
8. Merger of Electronics and Photonics Using Silicon Based Technologies (MEPHISTO)
   - STREP with 4 partners
   - The goals of MEPHISTO are to study and develop crucial, innovative enabling technologies and building blocks for realizing advanced silicon-on-insulator based optical motherboard subsystems that can be used in photonic networks.
9. Multi - Functional Integrated Arrays of Interferometric Switches (MUFINS)
   - STREP with 7 partners
   - MUFINS aims to demonstrate 2 and 4 element monolithically integrated arrays of packaged and pigtailed InGaAsP, 2x2 all-optical switches on single InP substrates for operation at 10 and 40 Gbit/s.
10. Multi Service Access Everywhere (MUSE)
    - IP with 33 partners
    - The overall objective of MUSE is the research and development of a future low cost, full service access and edge network, which enables the ubiquitous delivery of broadband services to every European citizen.
11. Network of Excellence for Micro-Optics (NEMO)
    - NoE with 29 partners
    - This Network of Excellence aims at providing Europe with a complete Micro-Optics food-chain, by setting up centers for Optical Modeling and Design; Measurement and Instrumentation; Mastering, Prototyping and Replication; Hybrid Integration and Packaging; Reliability and Standardization.
12. Nitride Intersubband Devices at Telecommunication Wavelengths (NITWAVE)
    - STRIP with 8 partners
    - This project aims at investigating the building blocks of an emerging semiconductor technology for ultra-high bit rate optoelectronic devices operating at fibre-optics telecommunication wavelengths. The advanced materials investigated are nitride-based heterostructures (GaN/Al(Ga)N, GaN/AlInN).
13. Next generation Optical network for Broadband in Europe (NOBEL)
    - IP with 31 partners
    - The main goal of the IP NOBEL is to carry out analyses, feasibility studies, and experimental validations of innovative network solutions and technologies for intelligent and flexible optical networks, thereby enabling broadband for all.
14. Wide Wavelength light sources for public Welfare: high BRIGHtness laser diodes for Telecom, medical, and Environment Use (WWW.BRIGHT.EU)
    - IP with 20 partners
    - The project mobilizes the expertise of the main European actors of the laser diode core technology and couples it with highly innovative optical technologies such as smart cavity concepts for higher efficiency and tuneability.

In the following, two large European projects will be presented in more details.

European Network of Excellence e-Photon/ONe+

The Network of Excellence (NoE) e-Photon/ONe$^+$ [3] focuses on the “Broadband for All” strategic objective, targeting network-oriented and system-oriented aspects of the optically enabled Broadband. It builds upon existing coordination activities among universities and research centers active in optical networking and transmission.
This NoE covers the technical areas of in-building, access, metro, and core telecom networks. It directs and structures the research on network architectures, technologies and protocols. e-Photon/ONe$^+$ aims at integrating and coordinating the European research assets to further build up the critical mass that is required today to compete in the global market.
The partners within e-Photon/ONe$^+$ come from a large number of European countries (17), mainly from member states (14 EU countries), including new member countries (Hungary and Poland), but also from candidate countries (Turkey and Croatia) and from Norway (associated country). This broad geographic diversity reflects also the diversity of research and teaching approaches and the diversity of the available infrastructure. This NoE has the capacity to provide better access to high-end infrastructures, even for researchers from countries or institutes where cutting edge lab facilities may not be available. It supports versatile optical telecommunications training all over Europe; it promotes the highest academic standards. An outcome of this would be overall awareness and consensus on the optical Broadband capabilities. This process will eventually provide guidance to the introduction of broadband access for all European companies, government institutions and households.

For the exploitation of knowledge, the consortium relies on the internal exchange of information with the industrial partners, but also intends to establish regular contacts with the European industry associations, e.g. operator associations such as EURESCOM, regulatory institutions, the European Optoelectronics Industry Consortium (or EPIC), and other relevant parties. At the same time interaction is performed with the IST BREAD project and strong involvement to the concentration activities.

The technical topics covered in both research and training are:

- Core networks - technologies, architectures, and protocols, including
  - switching technologies,
  - optical signal monitoring, and
  - network architectures.
- Metro networks - technologies, architectures, and protocols, including
  - distributed and centralized resource allocation and quality of service control schemes,
  - advanced all-optical WDM architectures including a.o.: dynamic optical circuit switched networks, and optical packet switched networks,
  - short-term techno-economical comparisons and assessments, and
  - migration scenarios and economical ways to introduce optical functionality.
- Access networks - technologies, architectures, and protocols, including
  - fiber-wireless,
  - fiber-coax, and
  - coarse WDM.
- Home networks and other short-reach networks, including
  - protocols,
  - cost-effective transmission, and
  - plastic fiber applications.
- Optical and opto-electronic switching systems - cross connects, burst switches, packet switches, including
  - all-optical and optoelectronic switching technologies and architectures,
  - label generation, swapping, and detection,
  - optical packet/burst switching and routing, and
  - synchronous vs. asynchronous packet operation.
- Transmission techniques for broadband networks, including
  - new modulation formats, with specific focus on resilience to impairments,
  - electronic compensations of dispersion and other linear and non-linear fiber and network node impairments,
  - bandwidth efficient transmission,
  - amplification schemes supporting WDM transmission in transparent reconfigurable networks, and
  - optical and electronic enablers fostering the actual commercial deployment of 40 Gbit/s.

Integration activities regarding these topics are organized in thematic structures called Virtual Departments (VDs), which were already successfully implemented in the first phase of this NoE. Regarding the technological part, both a transversal and a vertical integration are envisaged. The former enables the use of a wide range of high-end design, fabrication and characterization tools in the technology developments on the network level, the system level and the components level. The latter ensures that knowledge about limitations and requirements in one sub-area can be articulated to have impact in other sub-areas.

COST Action no. 291: Towards Digital Optical Networks

The primary objective of the COST Action “Towards Digital Optical Networks” [4] is to focus on novel network concepts and architectures exploiting the features and properties of photonic technologies that enable future telecommunications networks. It is aiming to propose a new generation of systems and networks that will accommodate the unpredictable and growing size of data files and messages exchanged and stored as well as real time services (e.g. voice, video etc.) over global distances requiring an agile Communication Grid supporting quality services. These need to provide end-to-end bandwidth for transmission of traffic for applications such as information retrieval, downloading (often multimedia) web software, exchange of various type of software (hundreds of MBytes) and data models (GBytes) as well as real time multimedia applications.

These systems need to be very flexible and rapidly reactive to efficiently accommodate the abrupt and unpredictable changes in traffic statistics induced by current and future applications with low end-to-end latency. They will enable advanced features such as efficient and simple multicasting and broadcasting of broadband signals. In general, they need to support a future proof, flexible, efficient, and bandwidth-abundant fibre-optic network infrastructure capable of supporting ubiquitous services in a resilient manner offering protection and restoration capabilities as well as secure services to the users.

Transparency to various digital signals and protocols is required to eliminate the need for multilayer complex network architectures suffering from poor scalability for data services, high latency, complicated network management, and high cost. This migration can be gradually achieved by removing and/or integrating intermediate layers. Flat and upgradeable network architectures supporting photonic core and access technologies with intelligent edge nodes at the interfaces will form a universal infrastructure offering a variety of services supported by multiple operators. The ease of maintenance, provisioning and resilient operation required in this type of networks will be achieved through advanced routing and management mechanisms, eliminating the requirement for ever increasing amounts of complex software responsible for raising the cost and limiting the network reliability and availability.

This advanced photonic infrastructure will use optical signal processing and dynamic impairment management to eliminate the limitations of the analogue nature of traditional optical networks. Additionally to the dense wavelength division multiplexing technologies, they can be used for signal transmission and routing as well as for optical packet and/or burst switching, in order to provide fine bandwidth granularity, high network efficiency, and large flexibility.

There are three working groups (WGs) that are active as task forces throughout the entire project duration, dealing with the most urgent work in these domains:

- WG1: "Optical processing for digital network performance". This workgroup focuses on physical layer and implementation related issues of transparent optical networks and covers advanced topics such as optical signal per bit processing, optical switch architecture designs and implementations as well as transmission related issues.
- WG2: "Novel network architectures". This workgroup focuses on the evolution of network scenarios including the study of novel network architectures. This workgroup also studies different node architectures and technologies in terms of network performance and functionality. Three different architectures are studied and compared: circuit- (wavelength, waveband, etc.), optical burst-, and optical packet-switched networks.
- WG3: "Unified control plane, network resilience and service security". This workgroup focuses on two directions. The former deals with the impact of transparency on photonic network architectures and the associated control and protocol issues. The latter focuses on network survivability and security issues, covering topics such as protection and restoration, its impact on routing and wavelength assignment algorithms, fault isolation, disaster recovery, etc.

The Action is open to collaboration and co-ordination with other ongoing or future COST Actions in the domains of optics, optoelectronics, and other related networks technologies such as radio and satellite. In particular, an information exchange is initiated with COST 288 and 270 in order to discuss topics associated with specific technologies and optical network availability and reliability issues. The Action has also established links and connections with different standardisation bodies such as ITU Study Group 15, IEC Technical Committee 86, etc. In addition, cooperation with the project OPTIMIST, coordinating the photonic domain activities within FP5 and any follow-up activity within FP6 (e.g. BREAD, Evergrow, e-Photon/ONe+), has been already established in order to achieve continuous information exchange and close interaction with all the related Actions supported by the EU.

3. TOWARDS DIGITAL OPTICAL INTERNET

High-speed packet-switched optical networks may be a natural choice when some users in a network occasionally require very high data rate (according to the bandwidth-on-demand principle). Introducing a new design strategy for access nodes and using all-optical processing techniques as well as high-speed electronics, medium access nodes capable of handling very high data rates can be designed [5].

Based on the development of enabling technology, optical network functionality has made progress from simple point-to-point WDM links to automatically switched optical network (ASON) and multi-layer switching (e.g. automatically switched transport network - ASTN) as shown in Figure 2. In the future, dynamic burst-switched and packet-switched photonic networks may be expected.

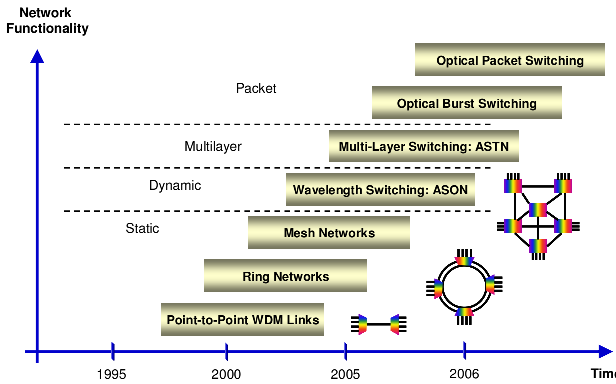

Figure 2: Evolution of optical network functionality (WDM: Wavelength-Division Multiplexing, ASON: Automatically Switched Optical Network, ASTN: Automatically Switched Transport Network)

Relying on the processing technology that is available today, the network nodes operate with up to 40 Gbit/s electronics. In the future, the network nodes should be able to accept data beyond 100 Gbit/s. At such high bit rates, signal processing in the electrical domain is very difficult to realize. To overcome the electronic processing bottleneck, high-speed all-optical signal processing has to be used in network nodes.

All-optical networks allow optical signals to remain in an optical format on their route between source and destination. By avoiding the bottleneck due to the electro-optic and optoelectronic conversions, this type of networks can provide high bandwidth, bit rate/format transparency, and fault-tolerant communications. In principle, there are two types of all-optical networks: circuit-switched and packet-switched. The circuit-switched networks are in general less efficient than the packet-switched networks because packet switching allows a more efficient use of the available bandwidth by dividing it into small portions, i.e., into frames or packets, which can be assigned to the network nodes in a dynamical manner. On the other hand, the circuit-switched all-optical networks are easier to realize then the packet-switched one. This is because they can be implemented by using the state-of-the-art optical multiplexing and switching technologies. Nowadays, there are already network components and systems on the market that are capable of supporting switching of circuits in the optical domain.

Currently, obvious research efforts are aiming at optical burst-switched networks. Optical burst switching is a promising hybrid approach between optical circuit switching and optical packet switching. Here, the control plane is separated from the data plane. This is done by using a dedicated control channel for transmission of header cells. The header cells, which contain the control information, precede the data bursts, so that the resource allocation is requested at each burst switching node to be traversed. If the capacity reservation was successful, the burst can be transmitted without collisions.
By employing the processing in the optical domain, very high-speed access to the optical fiber even at Tbit/s rates can be achieved. In this context, ultra-fast optical switching, optical packet rate conversion, and all-optical header recognition may play an important role in the future. On the one hand, all-optical header recognition will allow packets to remain in an optical format until they arrive at their destination, so the throughput bottleneck caused by the electronic processing can be eliminated. On the other hand, by the use of the so-called optical rate-conversion technique, very high-speed access to the optical medium could be possible.
All-optical packet-switched and burst-switched networks could be used to satisfy the enormous demand on bandwidth in the Next-Generation Internet. It is imaginable to use the all-optical networks for applications such as multimedia, telemedicine, high-speed access to large databases, clustering, grid computing, and in realizing high-performance storage area networks (SANs), especially when several local SANs need to be connected over very large distances (distant SANs).

8. CONCLUSIONS

New all-optical technologies will allow the design of ultra high-speed photonic networks that can provide a high capacity for the next generation Internet in a dynamical manner. In this paper, an overview on research landscape in Europe in the area of photonic networks is presented. In particular, two large European projects, namely a network of excellence and a COST action, are presented in more detail.
Approaches towards all-optical techniques contribute to a better utilization of transmission capacity of optical fibers. The fast growth of aggregated Internet traffic and development of new telecommunications applications can only be satisfied by developing novel photonic network technologies that can provide high capacity and an efficient transport of heterogeneous network traffic. Such networks will be able to support any future application. The photonic network technologies in interaction with advanced wireless technologies and applications will open the door into a new era of high-speed and high-performance communications and information processing systems.

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Slavisa Aleksic received the Dipl.-Ing. and the PhD degrees in Electrical Engineering from the Vienna University of Technology, Austria, in 1999 and 2004, respectively. Currently, he is employed as an Assistant Professor at the Institute of Broadband Communications, Vienna University of Technology, where he is responsible for teaching and research activities. His current research interests include communication networks, photonic networks, high-speed optical and electrical signal processing systems as well as high-speed media access control (MAC) protocol design and implementation.
Dr. Aleksis is author or co-author of more than 25 scientific publications including books, papers in peer-reviewed scientific journals, and contributions to international recognized conferences. He has a great experience in both research and industrial fields through successfully managing and conducting many projects related to communication networks including two projects funded by the Austrian Science Fund (FWF) and a number of projects in collaboration with several Austrian and European academic institutions and companies. He is a member of the Management Committee in the COST action no. 291 „Towards Digital Optical Internet" and leader of the Austrian research group within the EU Network of Excellence "e-Photon/One+".
Slavisa Aleksic is a member of the Institute of Electrical and Electronics Engineers (IEEE - USA), of the Austrian Electrotechnical Association (OVE - Austria), and of the Institute of Electronics, Information and Communication Engineers (IEICE – Japan). He received several international awards, grants, and recognitions.