Next-Generation Optical Access Networks: Dynamic Bandwidth Allocation, Resource Use Optimization, and QoS Improvements

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Rapidly increasing traffic demands of current residential and business applications and newly evolving services require access network solutions that can offer dramatically higher bandwidth. New applications tend to be media-rich such as high-definition television (HDTV), video on demand (VoD), voice over IP (VoIP), and high-speed Internet. Emerging applications include multimedia conferencing, multiplayer online gaming, online content generation, and consumer-oriented cloud-computing solutions, and are even more demanding and bandwidth-hungry. As a result, future wireline access networks will be faced with the challenge of transporting the ever increasing volume of data-centric traffic with ever tighter timing and quality of service (QoS) requirements.

In the access network domain, over the next few years, the copper and coaxial links (which currently constitute the majority of installed infrastructure) will be replaced by optical fibers, and the fiber-based networks will move closer to the customers using a variety of next-generation access architectures, including fiber to the building (FTTB) and fiber to the home (FTTH). Customers can and will require new communication services with a high availability and quick data down- and upload.

Present FTTH optical access systems mainly use point-to-point (PtP) and passive optical network (PON) technologies. Current commercially available PON solutions are based on time-division multiple access (TDMA), such as the XGPON, GPON, and EPON standards. Research is underway to support higher bit rates, reduce latency, extend reach, and enhance splitting ratios; this will enable a substantial reduction of the number of central offices.

Exploration of other technologies (e.g., WDM, OFDMA, UDWDM, OCDMA, and hybrid solutions) for next-generation optical access is currently the focus of many research activities and projects worldwide. The latest proposed solutions are expected to simplify the implementation and development of scalable access networks essential to support both the ongoing service upgrades and next-generation rich multimedia content ranging from 100 Mb/s to multiple gigabits per second per access subscriber.

Although the escalating demand in bandwidth provision could be met by wireline networking solutions, next-generation access networks should also provide end users with great flexibility and mobility. The convergence of fixed and mobile networks is likely to deliver the desired benefits of data-centric high-quality mobile service offerings with greatly improved performance compared to today's approaches. This convergence will pose a fundamental challenge to future access/metro networks where transparent integration of wireless and optical services and the simultaneous introduction of dynamic multiwavelength transmission need to be achieved.

Many diverse research activities are taking place around the globe to address the above mentioned challenges. To review the recent research developments in next-generation optical access networks, we have prepared a dedicated special issue of *IEEE Network* that includes high-quality contributed articles accepted from an open call for papers. We have selected for publication several outstanding articles addressing the following topics:

- Next-generation medium access control (MAC) algorithms and protocols
- Architectures/technologies offering sustainable ultra-high bit rate per user
- Energy efficiency issues
- Protection/restoration issues
- Techniques to improve QoS guarantees
- Hybrid/converged wireline/wireless access network architectures
- Graceful evolution of legacy PONs to next-generation (NG)-PONs

As a result of the call for papers, we received a total of 27 submitted papers. Following two rounds of a scrutinizing review process, seven articles were accepted to appear in the March/April 2012 issue of *IEEE Network*. The accepted manuscripts are top-quality and represent good coverage of the topics the special issue intended to cover.

The first article is authored by participants of the operator group at the International Telecommunication Union Telecommunication Standardization Sector (ITU-T) full service access network (FSAN) working group investigating the architectures and technologies for the next generation of optical access networks. It is entitled "Network Operator Requirements for the Next Generation of Optical Access Networks," and discusses the requirements and targeted specifications for the so-called NG-PON2 standard currently in the definition phase. The authors present their insightful views on the relevant open issues and challenges with the goal of informing the scientific and engineering communities, and preparing the ground for promoting mature contributions into ITU-T in order to finalize the relevant standard.

In the article "NG-PONs 1&2 and Beyond: The Dawn of the Über-FiWi Network," the authors first present a review of major progress in NG-PON 1 and 2 technologies. Major candidate NG-PON 1 and 2 architectures are discussed, including long-reach XG-PON, wavelength-routing WDM PON, and OCDMA and OFDMA PON. The authors then go on to discuss converged optical fiber-wireless (FiWi) access networks, claiming them to be the possible endgame of broadband access. According to the authors, powerful layer 2 optical-wireless, hierarchical frame aggregation, and network coding techniques can improve NG-PON and FiWi networks in terms of throughput-delay performance, resource utilization efficiency, and survivability. Finally, the authors propose a novel Über-FiWi network, and demonstrate its potential by studying the beneficial impact of inter-home scheduling of emerging plug-in electric vehicles (PEVs) on the resource management of a more sustainable future smart grid.

The article "Next-Generation Optical-Wireless Converged Network Architectures" presents a comprehensive analysis on implementing the next-generation optical-wireless integration architectures. The performance analysis shows that the proposed 10GEPON-LTE converged network architecture is a QoS-capable architecture suitable for next-generation optical-wireless converged networks.

The article "Energy Efficiency in the Extended-Reach Fiber-Wireless Access Networks" discusses the convergence of PONs and wireless access networks (FiWi) that combine the robustness and high capacity of optical networks with the mobility and ubiquity of wireless networks. This article presents an overview of energy-efficient protocols and design approaches in FiWi networks. The authors also propose an energy-efficient bandwidth allocation mechanism for FiWi. With simulation results, the authors demonstrate that the proposed scheme can provide significant energy savings in long-reach FiWi networks while overcoming the delay penalty caused by ONU-BS sleep modes. Also discussed in the article are the open issues and challenges of energy efficiency of FiWi networks and future research possibilities.

The authors of the article "Energy-Efficient PON with Sleep-Mode ONU: Progress, Challenges, and Solutions" focus on the fact that while enabling sleep mode in the ONU is among the most promising techniques for energy-efficient PONs, it brings many challenges including slow transition of power between two modes, and long recovery and synchronization time required by the wake-up process. In their article, a service level agreement (SLA)-based scheme for PONs is proposed to address these issues. With simulation results, the authors show that the proposed scheduling scheme provides significant energy saving and addresses the problem of frequent mode switching: the ONU is able to save 40 percent of the energy under moderate use and practical power consumption settings.

The article "Adaptable Access System: Pursuit of Ideal Future Access System Architecture" presents a concept of an adaptable access system. The R&D vision toward an adaptable, dependable, and eco-conscious access system is discussed. Next, three concepts of physical network infrastructures —active single star, service-area-variable minimum cellular, and access system virtualization — are presented and their technological targets highlighted.

Finally, the article "Medium Access Control for the Next Generation Passive Optical Networks: The OLIMAC Approach" introduces the concept of OLIMAC as an instructive technology enabler for NG-PON2 systems. The authors propose a solution to the MAC issue in NG-PON2 and explain its method of operation. Issues such as engineering aspects as well as interoperability are also discussed. A numerical simulation model is presented that validates the working of OLIMAC and showcases improvements in terms of network-wide utilization, channel blocking, as well as provisioning delay.

We are grateful to the authors, peer reviewers, and the magazine's Editorial Board and staff for their contributions to this Special Issue. We are thankful to Ms. Shixin Fu for her help with handling some reviewing and editing tasks. Lastly, we would especially like to acknowledge the strong support and guidance from *IEEE Network*'s previous Editor-in-Chief Prof. Tom Chen. We hope that this special issue is useful for the research community.

Biographies

IOANNIS TOMKOS [B.Sc., M.Sc., Ph.D.] (itom@ait.gr) has been with the Athens Information Technology Center (AIT) since September 2002. In the past, he was an adjunct faculty member at the Information Networking Institute of Carnegie-Mellon University, Pittsburgh, Pennsylvania (2002–2010), senior scientist (1999–2002) at Corning Inc. USA, and research fellow (1995–1999) at the University of Athens, Greece. At AIT he founded and serves as head of the High Speed Networks and Optical Communication (NOC) Research Group that was/is involved in many EU funded research projects (including five active) within which he is representing AIT as Principal Investigator and has a consortium-wide leading role (e.g., Project Leader of the EU ICT STREP project DICONET, Project Leader of the EU ICT STREP project ACCORDANCE, Technical Manager of the EU ICT STREP project SOFI, Technical Manager of the EU IST STREP project TRIUMPH, Chairman of the EU COST 291 project, WP leader in many other projects). He is the Chairman of the Next Generation Networks working group of the Digital Greece 2020 Forum. He received in 2007 the prestigious title of Distinguished Lecturer of IEEE Communications Society on the topic of transparent optical networking. Together with his colleagues and students he has authored about 420 peer-reviewed archival articles (over 240 IEEE sponsored items), including over 110 journal/magazine/book publications and 310 conference/workshop proceedings papers. He has served as the Chair of the International Optical Networking Technical Committee of IEEE Communications Society (2007–2008) and the Chairman of the IFIP working group on "Photonic Networking" (2008–2009). He is currently the Chairman of the OSA Technical Group on Optical Communications (2009–2010) and the Chairman of the IEEE Photonics Society Greek Chapter (2010). He has been General Chair, Technical Program Chair, Sub-

committee Chair, Symposium Chair or/and member of the steering/organizing committees for the major conferences (e.g. OFC, ECOC, IEEE GlobeCom, IEEE ICC, ONDM, ICTON, BroadNets, etc.) in the area of telecommunications/networking (more than 100 conferences/workshops). In addition he is a member of the Editorial Boards of the *IEEE/OSA Journal of Lightwave Technology*, *IEEE/OSA Journal of Optical Communications and Networking*, *IET Journal on Optoelectronics*, and *International Journal on Telecommunications Management*. He is a Fellow of the IET.

LEONID G. KAZOVSKY [F] (network.kazovsky@stanford.edu) joined Stanford University in 1990. He founded the Photonics and Networking Research Laboratory (PNRL) at Stanford University and leads PNRL since establishing it in 1990. The PNRL research team includes some 15 researchers focused on green (energy-efficient) optical/wireless access and in-building networks. Prior to joining Stanford, he was with Bellcore doing research on coherent, WDM, high-speed, and other advanced optical fiber communication systems (later, Bellcore changed its name to Telcordia, and was acquired by Ericsson). His research of coherent optical systems at that time resulted in what is widely considered today as key foundations of modern coherent systems. While on Bellcore assignments or Stanford sabbaticals, he worked at the Heinrich Hertz Institute, Berlin, Germany; Hewlett-Packard Research Laboratories, Bristol, England; Technical University of Eindhoven, the Netherlands; Scuola Superiore St. Anne, Pisa, Italy; Danish Technical University, Copenhagen, Denmark; and Acreo, Stockholm, Sweden. Through research contracts, consulting engagements, and other arrangements, he has worked with many industrial companies and U.S. government agencies including Corning, Alcatel-Lucent, Sprint, DT, Huawei, DEC, GTE, AT&T, IVP, Lucent, Hitachi, KDD, Furukawa, Fujitsu, Optivision, and Perimeter on the industrial side; and NSF, DARPA, Air Force, Navy, Army, and BMDO on the government side. He also worked extensively with many leading VCs and intellectual property law firms. He serves or served on Editorial Boards of leading journals (*IEEE Transactions on Communications*, *IEEE Photonics Technology Letters*, *Wireless Networks*) and on Program Committees of leading conferences (OFC, CLEO, LEOS, SPIE, and GLOBECOM). He also served as a reviewer for various IEEE and IEE transactions, proceedings, and journals; funding agencies (NSF, OFC, ERC, NRC, etc.), and publishers (Wiley, MacMillan, etc.). Recently, he organized several workshops on hybrid optical/wireless networks at OFC and WCNC; he also co-edited a Special Issue of *IEEE Network* on Next Generation Optical Access Networks. He has authored or co-authored three books, three book chapters, 55 invited journal papers and invited conference talks, some 200 journal technical papers, and some 300 conference papers. His latest book, *Broadband Optical Access Networks*, was published by Wiley in 2011. His most recent invited paper on hybrid optical/wireless networks will be published in *Proceedings of IEEE* in 2012. He is a Fellow of OSA.

KEN-ICHI KITAYAMA [F] (kitayama@comm.eng.osaka-u.ac.jp) received M.E. and Dr.Eng. degrees in communication engineering from Osaka University, Japan, in 1976 and 1981, respectively. In 1976 he joined the NTT Laboratory. In 1995 he joined the Communications Research Laboratory (currently, NICT), Tokyo, Japan. Since 1999 he has been a professor with the Department of Electrical, Electronic, and Information Engineering, Graduate School of Engineering, Osaka University. His research interests are in photonic label switching such as packet/flow/burst switching, optical signal processing, next-generation OCDMA and OFDMA access systems, and radio-over-fiber communications. He has published over 260 papers in refereed journals, written two book chapters, and translated one book. He holds more than 40 patents. He currently serves on the Editorial Boards of the *Journal of Lightwave Technology*, *Journal of Optical Communications and Networking*, and *Optical Switching and Networking* as an Associate Editor. He is also currently serving as the Vice-President of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan. He has served as Guest Editor for special issues, including the *Journal of the Optical Society of America B* on Innovative Physical Approaches to the Temporal or Spectral Control of Optical Signals in 2002, *IEEE Journal on Selected Topics in Quantum Electronics* on Optical Code in Optical Communications and Networks in 2007, *IEEE/OSA Journal of Lightwave Technology* on Convergence of Optical Wireless Networks in 2007, and several more. He is a Fellow of IEICE of Japan.