A Survey on Radio-and-Fiber FiWi Network Architectures

T. Tsagklas and F. N. Pavlidou

Abstract— **The ultimate goal of Fiber-Wireless (FiWi) networks is the convergence of various optical and wireless technologies under a single infrastructure in order to take advantage of their complementary features and therefore provide a network capable of supporting bandwidth-hungry emerging applications in a seamless way for both fixed and mobile clients. This article surveys possible FiWi network architectures that are based on a Radio-and-Fiber (R&F) network integration, an approach that is different compared to the Radio-over-Fiber (RoF) proposal. The survey distinguishes FiWi R&F architectures based on a three-level network deployment of different optical or wireless technologies and classifies them into three main categories based on the technology used in the first level network. Future research challenges that should be explored in order to achieve a feasible FiWi R&F architecture are also discussed.**

Index Terms — **FiWi, R&F, Hybrid, Access Networks.**

I. Introduction

Technological evolution gave rise to new demanding applications and services that copper-based access networks cannot support efficiently. High Definition IPTV (HD IPTV), Video-On-Demand (VoD) and Online Interactive Gaming are only some of the services that require data rates up to tens of Mbps per client. This has led many providers to seek alternative mediums and infrastructures that would be able to provide such large capacities in the access network. Optical technology was adopted by many providers, since fiber is a medium capable of supporting services with rates in the Gbps region.

Apart from fixed optical networks, wireless broadband access networks have attracted a great deal of attention due to their low implementation costs and mobility support. WiFi-based Wireless LANs have undoubtedly dominated the wireless local area network market while cellular communication networks have also seen a huge growth especially after the recent commercial success of smartphones, which has increased even more the number of mobile broadband subscribers. Moreover, new emerging wireless standards like WiMAX were designed to support broadband services with high data rates and seamless mobility over large distances.

Optical networks offer a huge capacity but with high implementation costs while wireless networks offer mobility and ubiquity but in lower rates and via error-prone channels. The idea of combining these two networks is very attractive since it would allow the exploitation of the complementary benefits of both technologies. This led to the FiWi (Fiber-Wireless) network proposal where optical and wireless technologies form a common integrated infrastructure capable of supporting upcoming applications and services while offering seamless mobility to clients.

Two approaches are investigated for the integration of optical and wireless networks under the FiWi concept; Radio-over-Fiber (RoF) and Radio-and-Fiber (R&F). RoF technology is not a new concept; it dates back almost three decades with one of the first studies being conducted in 1984 by the Military Electronics Division of the TRW Electro Optics Research Center in California [1]. On the other hand, research upon R&F networks has only started during the last decade.

In RoF systems RF signals that modulate an optical carrier in a Central Office (CO) are being propagated over an analog fiber link to Remote Antenna Units (RAUs) and are then transmitted to clients through the air (Fig. 1).

RoF technology is based on a centralized signal processing functionality where network complexity is moved to a central location and thus the overall implementation cost

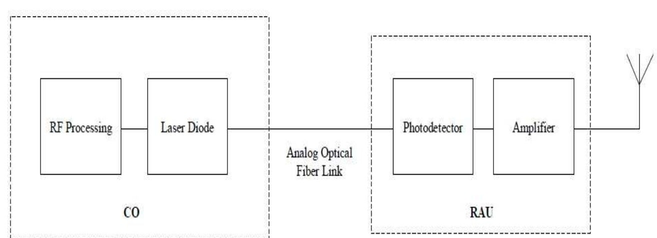

Fig. 1. Radio-over-Fiber FiWi concept

is reduced mainly because RAUs contain fewer components due to their simpler functionality. Resource allocation can be

Manuscript received March 4, 2011.
T. Tsagklas is with the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Campus 54124 Greece (+306930356638; e-mail: tsagklas@auth.gr).
F. N. Pavlidou is with the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Campus 54124 Greece (e-mail: niovi@auth.gr).

done more efficiently from a centralized unit while handover and operational-maintenance procedures become simpler. Moreover, the use of more simplified RAUs helps reduce the overall power consumption which is an increasingly critical factor in current and future network deployments.

In R&F, discrete optical and wireless networks are merged in order to form one single integrated network (Fig. 2).

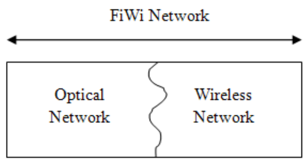

Fig. 2. Radio-over-Fiber FiWi concept

In general, R&F networks make use of different MAC protocols in the two parts of the network and therefore the access control of clients is done separately [2]. This means that traffic generated from users communicating only in the wireless network does not have to be propagated towards the optical network as happens with RoF technology. Thus, distributed MAC protocols, e.g. IEEE 802.11b, avoid the fiber's extra propagation delays that degrade their performance. This feature removes a possible limitation regarding the length of the deployed fiber while it adds a degree of resiliency to the system since local wireless traffic can be served even when connectivity with the optical segment is lost.

This survey deals only with R&F architectures mainly because all the processing in RoF is moved towards the CO which in our opinion is of high risk since this point can become a possible bottleneck for the access network, while additionally a possible failure inside the CO will endanger overall service availability.

The remainder of this article is organized as follows. Sections II and III present the optical and wireless enabling technologies for FiWi networks and their latest developments. Section IV introduces a possible classification of the FiWi R&F architectures while some already studied architectures are also presented. FiWi R&F research challenges are discussed in section V while section VI concludes the survey.

II. OPTICAL ACCESS NETWORKS

A growing number of providers worldwide are adopting optical technologies in the access network and towards the client's premises (Fiber-to-the-Home or FTTH) due to optical fiber's ability to provide huge amounts of bandwidth in longer distances than copper, immunity to electromagnetic interference and inherent security. Fiber generally should be installed underground for safety reasons and therefore its deployment is an expensive procedure. This is mitigated by deploying a tree-like network topology where a part of it is being shared by many clients (Fig. 3). Each client is connected

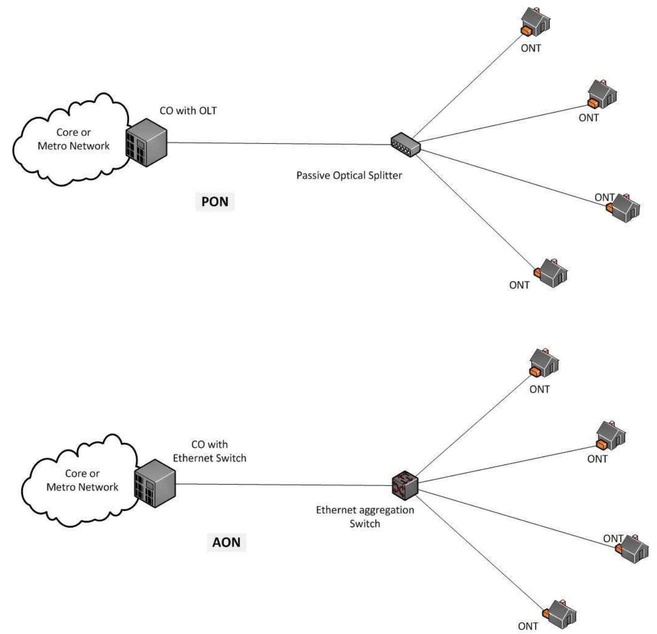

Fig. 3. PON and AON Optical Access Networks (Tree topology)

via a dedicated fiber to a Remote Node (RN) which in turn is connected via a single fiber to a CO. In general two technologies can be used for this implementation: Passive Optical Networks (PONs) and Active Optical Networks (AONs). Both terminate to an Optical Network Terminator (ONT) residing on a single client's premises or an Optical Network Unit (ONU) in the case of a building or office where multiple clients exist. ONUs are more complicated devices and therefore more expensive than ONTs.

A. PONs

In PONs the CO contains the Optical Line Terminal (OLT) which controls traffic in both directions while the RN consists of a passive optical splitter/combiner which requires no power for its functionality and usually supports 32 or 64 clients. In the downstream PONs are point-to-multipoint systems and therefore Time Division Multiplexing (TDM) is used for sending data to clients in a broadcast manner where all traffic is passed to all clients and the ONT is responsible to accept only the appropriate packets and discard the rest. In the upstream the system is multipoint-to-point and Time Division Multiple Access (TDMA) is used at the optical combiner in order to provide access to all users. Two TDM-PON standards are mainly implemented today; the IEEE 802.3ah (EPON) and the ITU-T G.984 (GPON). EPON carries Ethernet frames with symmetric rates equal to 1.25 Gbps while GPON carries several different data types (ATM, Ethernet, TDM), with the use of a Generic Encapsulation Method (GEM), supporting 2.488 Gbps rate in the downstream and 1.244 Gbps rate in the upstream.

Although the offered capacity from these standards is quite large, the growing demands of new applications forced these organizations to seek ways for increasing even more the available bandwidth. Two candidates were proposed for upgrading and eventually replacing 1 Gbps TDM-PONs; 10G TDM-PONs and WDM-PONs (Wavelength Division Multiplexing PONs). 10G TDM-PONs have already been standardized leading to 802.3av (10G EPON) and G.987 (10G GPON) standards respectively. These standards offer symmetric and asymmetric line rates up to 10 Gbps and are fully backward-compatible with legacy PONs allowing a joint operation of old and new technologies.

In WDM-PONs multiple wavelengths are supported over one single fiber allowing each user to exploit all of the fiber's bandwidth towards the CO (point-to-point link). In WDM-PONs the passive optical splitter is replaced by an Arrayed Waveguide Grating (AWG) which functions as a passive wavelength router. This introduces many benefits like increased network capacity, scalability, security, transparency regarding protocols and modulation schemes, and separation of services and service providers over the same infrastructure.

B. Developments in PONs

Future research on 10G TDM-PONs focuses on the technical feasibility of both individual components and integrated systems [3]. The main interest regarding components lies on the design of optical burst-mode transceivers for the upstream data transmission which is by nature bursty since users do not send data continuously but rather at random times.

On the other hand some interesting initiatives were formed in Europe in order to study WDM-PON technologies. Scalable Advanced Ring-based passive Dense Access Network Architecture (SARDANA) [4] will provide a scalable and robustness hybrid WDM/TDM multi-operator architecture aiming to extend both network performance and range. Furthermore, GigaWaM project [5] aims to provide innovative, low-cost and highly integrated optical components that will be used in order to scale up and upgrade existing PON networks.

C. AONs

AONs make use of Ethernet aggregation switches both at the CO and the RN exploiting in this way the intelligence of these devices. In the downstream the switch forwards traffic only to the appropriate recipient while in the upstream it has the ability to groom traffic from different clients and pass it towards the CO. Ethernet contains various IEEE standards supporting several different physical layer standards and data rates. IEEE 802.3z standard (Gigabit Ethernet) with its 1000BASE-BX10 physical layer supports up to 1 Gb/s rates over one fiber in 10 Km distance. Network capacity can be increased even more by using 802.3ae standard (10 Gigabit Ethernet) in the feeder fiber that connects the RN to the CO allowing in this way the aggregation of several Gbits of traffic from clients.

III. WIRELESS ACCESS NETWORKS

A. Wi-Fi

The IEEE 802.11x (x = a, b, g) family of standards is the technology that has dominated the wireless local area networking (WLAN) market worldwide in the last decade. These standards support the WLAN functionality where one Access Point (AP) is able to serve several users in a range of 100m indoor to 400m outdoor in a PMP topology with rates up to 54 Mbps (802.11g). The need for more bandwidth forced IEEE to create a new amendment which would increase dramatically the throughput capabilities of the standard. This led to the 802.11n amendment which is capable of achieving a theoretical maximum throughput of 600 Mbps [6] and which is backward compatible with other 802.11 legacy devices. In order to support such high throughputs some enhancements both at the PHY and the MAC layers of the legacy 802.11-2007 standard are introduced. At the PHY layer Multiple Input Multiple Output (MIMO) operation is used to provide spatial multiplexing and diversity with the use of up to four antennas maximum. The new standard allows an optional use of 40 MHz channels geminating in this way the data rate while Low Density Parity Check (LDPC) is used for error correction. The greatest enhancement at the MAC layer is Frame Aggregation which allows multiple frames, destined to the same receiver, to be added in a larger frame and to be acknowledged by one single ACK packet reducing in this way the overhead introduced in the network.

B. WiMAX

Worldwide Interoperability for Microwave Access (WiMAX) is a communications system able to provide wireless broadband access to users based on the IEEE 802.16 standards. The first edition of the standard supported only fixed users with theoretical data rates close to 75 Mbps in a maximum range of 50 Km. The 802.16e-2005 amendment (Mobile WiMAX) added support for mobile users in a range of 5-15 Km with maximum theoretical rates up to 30 Mbps. All these publications were superseded by the most recent 802.16-2009 edition which supports both PMP and WMN topologies. Furthermore, 802.16j-2009 was created in order to provide WiMAX with multihop relaying capabilities leading to coverage extension and capacity increase.

C. Developments in Wireless Networks

Although 802.11 standards are already widely deployed their functionality was not optimized for WMNs. Therefore the 802.11s amendment is being studied by IEEE in order to provide WLANs with important mesh capabilities [7]. Many issues relating to, frame structure, mesh network formation and management, synchronization and power management are addressed in this standard. Mesh Coordination Function (MCF) is implemented for users' multiple access while the optional Mesh Coordinated Channel Access (MCCA) protocol is used for QoS enhancement. Congestion control can also be implemented with stations asking from their neighbors to slow down their transmission rate. Security is an important issue in WMNs and thus 802.11s uses an algorithm that provides link-by-link independent security. Furthermore, a very important issue in mesh networks is path selection. 802.11s suggests the use of specific path selection algorithms although vendors are free to deploy their own protocols.

As we move towards the 4th Generation Wireless Era emerging applications and services present new challenges to providers. This led ITU to introduce the so-called IMT-Advanced concept which sets specific requirements that a standard must satisfy in order to be accepted as 4G [8]. Based on these recommendations IEEE works on the new 802.16m amendment which adds many enhancements while being backward compatible with previous WiMAX standards. It will support various MIMO schemes, QoS, Multi-hop Relaying, which allows for range extension and avoidance of coverage holes and Multi-Carrier Aggregation where one or more clients may use more than one channels, depending on channel availability, increasing in this way the data rates up to 100 Mb/s for mobile clients and 1 Gb/s for fixed clients.

IV. FIWI R&F ARCHITECTURES

The existence of various optical and wireless technologies results to several different combinations which might support a reliable and efficient R&F FiWi architecture. This section presents a classification of these architectures based on a three-level separation as we move from the core/metropolitan network towards the clients. Architectures are placed into two categories based on whether the chosen technology for the 1st level of the network is optical (PON/AON) or wireless (WiMAX).

Table 1 presents this classification by showing the selected technology at each network level. In both cases the root of the FiWi network is connected to an optical Core or Metropolitan network which might use various technologies (WDM, Optical Burst Switching, Resilient Packet Ring, etc) and topologies (Ring, Mesh, etc). In most of the architectures, the devices residing in the borders between two different networking technologies are considered to be hybrid as will be explained in the later sections.

TABLE I
CLASSIFICATION OF FIWI ARCHITECTURES

Network Technology				FiWi Architectures
Core/Metro	1st Level	2nd level	3rd level	
Optical (WDM, RPR, OBS)	PON (TDM/WDM)	WMN		Figure 4
		WiMAX (802.16-2009)		
	PON (TDM/WDM)	WiMAX (802.16m)	WMN	
	AON	WMN		
		WiMAX (802.16-2009)		
	AON	WiMAX (802.16m)	WMN	
	WiMAX (802.16-2009)			Figure 5
	WiMAX (802.16m)	EPON		
	WiMAX (802.16m)	EPON	WMN	

A. PON Architectures

In this category the technology used in the 1st level is a TDM-PON (e.g. EPON) or WDM-PON or a combination of both. There are three different architectures that can be deployed in order to provide a FiWi access network depending on the technology at the 2nd and 3rd level of the access network (Fig. 4). All these cases have been already studied and discussed in the literature.

An EPON (1st level) and WiMAX (2nd level) generic integration was first proposed in [9] where tree different R&F architectures are examined: the Independent, where an ONU is connected to a WiMAX Base Station (BS) via a standard interface, the Hybrid, where the ONU and the BS are integrated both in hardware and software into one single device without any protocol modification and the Unified Connection-Oriented, which is similar to the Hybrid but with protocol modifications on the EPON side in order to be able to directly carry WiMAX data packets from the ONU to the OLT and backwards.

TDM-PON (1st level) and WiFi-based WMNs (2nd level) were extensively studied under the concept of WOBAN [10]. In WOBAN multiple OLTs, residing into a CO, support a number of ONUs scattered throughout a large geographic area. Each ONU is connected to a WiFi AP (like in the previous Independent architecture) which bridges the optical and wireless networks. Several other APs are scattered around in order to provide connectivity to wireless subscribers across the entire area. The efficiency of this architecture has great dependence on the overall network planning. In addition, many issues regarding routing traffic in the mesh network, network self-organization and survivability were investigated.

The third architecture which combines TMD/WDM-PON (1st level) with a WiMAX metro network (2nd level) and a WiFi-based WMN access network (3rd level) can also be found in [11] as part of a more extensive proposal. In order to support the interoperation of all these different parts of the network, integration of nodes that reside between any two technologies is considered mandatory. An entity called QoS-Proxy is proposed which, apart from integrating nodes of different technologies, it is also responsible for providing QoS support at all parts of the network. In our approach we characterize the WiMAX part as "Metro" due to the fact that it is used to extend the overall coverage and also functions as a bridge between the PON network and the WMN network.

B. AON Architectures

As illustrated in Fig. 4 AON architectures are identical to PON architectures with the difference that Ethernet aggregation switches are used in the place of Optical Splitters or AWGs and inside the CO replacing the OLTs. AONs have not attracted the attention of academia to the same extent as PONs mainly because they are considered to be more costly in terms of CAPEX and OPEX and less power efficient. However, under a more careful and insightful comparison of PONs and AONs this opinion might be disputed. Both PONs and AONs require power at the CO and at the customer's

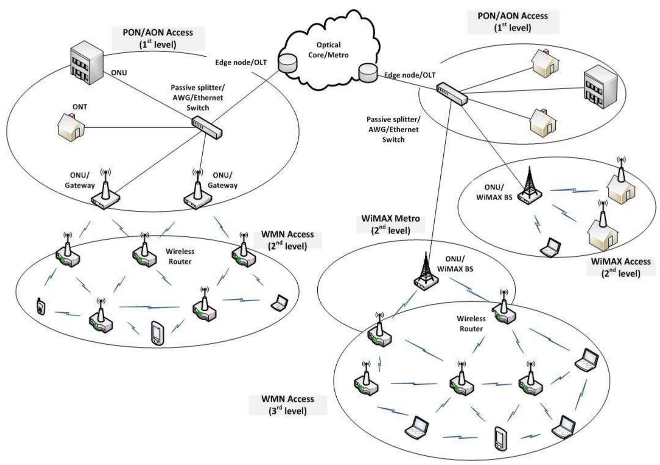

Fig. 4. Optical 1st level architectures

premises. The only actual difference between PONs and AONs regarding power consumption is the use of the Ethernet switch at the RN for AONs. However, this is counterbalanced by the advantage of using an intelligent device which is capable of switching local traffic, lightening in this way the upstream traffic sent from clients to the CO. In addition, in the downstream each client receives only the traffic destined to it which, apart from dealing with content delivery issues related to specific services; it also enhances the overall network security.

Therefore, both technologies have pros and cons and it is up to the network provider to decide which one best serves its needs. Under the FiWi concept where new research directions emerge we believe that AONs add some interesting and useful features that should be taken under consideration for future FiWi architectures.

C. *Wireless Architectures*

In this category of architectures broadband wireless technology and more precisely WiMAX standards in PMP mode are used in the 1st level. As illustrated in Fig. 5, a distinction of WiMAX networks into Access and Metropolitan takes place. This is used in the same aspect as in PON architectures meaning that WiMAX Metro serves as a bridge between the Core/Metro optical network and the networks in the 2nd and 3rd level.

The first architecture comprises of a WiMAX access network (1st level) which serves wireless fixed and mobile clients. One kind of this architecture can be found in [2] as part of a more extensive deployment where an IEEE 802.17 (RPR) Optical Metropolitan Ring network is used as a backbone for various access networks like hybrid EPON/WDM-PON and WiMAX. In our approach the optical core/metro network is considered to be in a more general form containing various technologies and topologies.

The second architecture consists of a WiMAX Metro network (1st level) and an EPON access network (2nd level) while the third architecture is similar to the second but with an additional WiFi-based WMN access network (3rd level). In both cases the IEEE 802.16m amendment is used as a WiMAX Metro network for two reasons. First, 802.16m has the ability to provide Multihop Relaying functionality where a central BS can communicate with a remote Relay Station (RS) in a Point-to-Point mode. In this way coverage extension can be achieved. Second, 802.16m with its Multi-Carrier Aggregation feature can achieve theoretical maximum data rates up to 1 Gb/s for fixed clients. By using such a network as a “backbone” for an EPON network we are able to provide a shared rate up to 1 Gb/s to PON clients in a distance of several tens of Kilometers.

The second and third architectures might be a good solution in cases where the deployment of optical fiber in the first few miles might be considered difficult due to geographical/morphological reasons, e.g. clusters of islands and distant highland villages, or where the investment of deploying fiber in some areas might be inexpedient due to high digging costs or even when possible regulatory restrictions regarding fiber deployment exist.

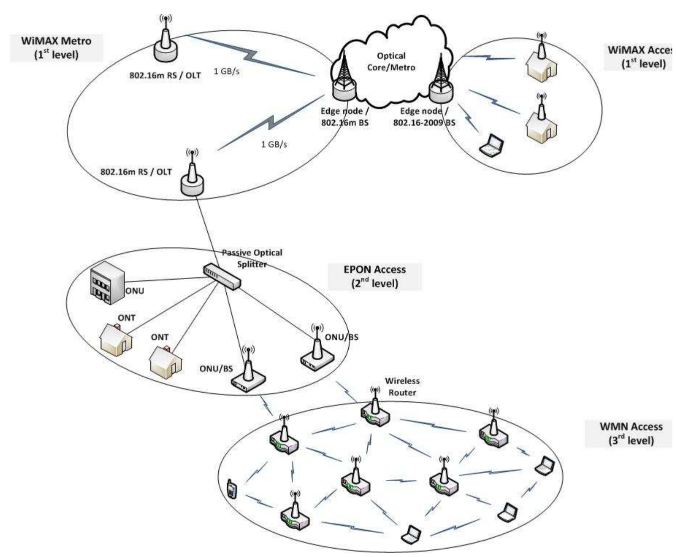

Fig. 5. Wireless 1st level architectures

V. RESEARCH CHALLENGES

A large number of FiWi architectures were proposed from both academia and private laboratories and this indicates their importance in future communication networks. However, many issues remain still open for research before a commercial deployment of this technology becomes a reality.

Various future research challenges of FiWi networks are discussed in [12]. An open issue in the PHY layer is the fabrication of hybrid devices that will be capable of supporting various different data types and will lead to the physical integration of optical and wireless technologies. This integration requires appropriate modifications of various physical interfaces in order to guarantee the reliable functionality of these devices while at the same time their cost should be kept low.

Each of the technologies adopted under the FiWi concept makes use of its own MAC protocol for serving client traffic. If these technologies work independently the huge amount of available resources that optical networks offer will be underutilized. Therefore the use of hybrid integrated MAC protocols is crucial in order to efficiently utilize the available resources and achieve a high overall network performance. These protocols must support end-to-end QoS so that Service Level Agreements (SLAs) are satisfied and clients receive guaranteed services. A lot of attention was paid so far to ways of mapping the QoS parameters between different technologies, e.g. matching of WiMAX Classes of Service with EPON queues, and to mechanisms that can dynamically allocate resources in an integrated manner by taking into account the resource availability at all network segments. However, for a truly end-to-end QoS support more research is required regarding the admission control of new clients in the network, based again on the overall resource availability, and the creation of efficient packet scheduling schemes, based on service differentiation and priority.

Routing is a very important issue in FiWi networks that comprise of WMNs since multi-hoping has a great impact on network performance degradation. Routing algorithms provide Layer-3 functionality and several efficient algorithms exist for reducing the number of hops in a WMN. However, these algorithms have no knowledge of the functionalities that take place at a lower level, e.g. resource allocation. Therefore a combined functionality of those two layers in terms of possible Layer-2 routing algorithms is needed in order for WMNs to exploit the huge available bandwidth provided by optical networks.

As the number of clients increases and new applications and services are developed the need for resilience and protection of future networks against failures in order to support their survivability is of highest interest. Resiliency is an inherent feature in networks with meshed topologies either in the optical or wireless segment due to the existence of several redundant connections between nodes. However, in order to exploit this feature, special mechanisms which will be able to redirect traffic efficiently must be devised. Apart from protection, the aforementioned implementations can also be used to enhance the overall network performance by terms of load-balancing when specific nodes or links are heavily loaded. The use of WDM technology can provide further resiliency by supporting reconfiguration functionalities at the optical network. This can be achieved by deploying appropriate wavelength allocation mechanisms that will take into account the overall resource availability and adjust resource allocation according to changing traffic demands.

Other research challenges relate to the network's capability to support peer-to-peer communication and multicasting. File sharing and peer-to-peer interactive games are examples of applications where users exchange large amounts of data. This kind of traffic can be served more efficiently by using decentralized resource allocation mechanisms in order to avoid possible network bottlenecks. On the other hand, in services like VoD and IPTV the same content must be delivered to multiple users. Therefore, multicast support, under which one unique flow is simultaneously transmitted to many users avoiding in this way waste of resources, is a crucial feature of current and future networks and must be explored in detail for FiWi networks.

Support of seamless mobility is also crucial, especially after the commercial success of smartphones which offer broadband services to mobile users. Therefore FiWi networks must provide simple and flexible handover operations that will be able to meet the QoS requirements of new emerging mobile applications.

Finally, an important issue regarding commercial FiWi network implementation is energy consumption. We have already described how FiWi networks introduce the need for hybrid devices in order to achieve a high-performance integrated optical-wireless network. As we move towards the Green IT Era it is crucial to study the energy consumption of such devices, especially since they will be equipped with new electronic modules, which will offer new functionalities, in order to support the aforementioned integration.

VI. CONCLUSIONS

Upcoming and future applications will change once and for all our perception of network infrastructures. With bandwidth demand being increased exponentially and with clients asking for seamless connectivity no matter where they are it is obvious that access networks will have to be enhanced with tremendous capabilities that were not needed in the past.

Both optical and wireless technologies were evolved throughout the last decades in terms of bandwidth capacity and QoS support of clients. Tens or even hundreds of Gb/s in large distances of several Kilometers were achieved with the use of optical fibers while broadband services have conquered also the wireless market domain. However both technologies present disadvantages which disincline them from being considered as the final solution for future network infrastructures.

On the other hand, FiWi networks comprise a new emerging technology that combines the advantages of both optical and wireless networks. Several optical and wireless technologies can be integrated under various architectures in order to provide high broadband accessibility to both fixed and mobile clients since the huge capacity of optical fibers can be combined with the flexibility that wireless networks offer.

One such approach is the concept of Radio-and-Fiber FiWi networks in which optical and wireless technologies, like PONs, AONs, WiMAX, etc are being integrated either in hardware or software leading to new hybrid network architectures. These architectures can be categorized based on the technology that is being used in various levels of the infrastructure as we move from the Core/Metropolitan network towards the client.

Many FiWi network architectures were already studied with researchers focusing mainly on subjects like QoS support, physical characteristics of new hybrid devices, routing algorithms that will allow wireless traffic to exploit the capacity offered by optical gateways, network resiliency which is crucial in order to support both uninterrupted services and load-balancing.

In addition, other issues that should be considered are the support of peer-to-peer communication and multicasting which both save network resources, support for user mobility and therefore efficient handover schemes, and energy consumption which is becoming increasingly vital nowadays.

In general, FiWi networks comprise a new research topic and therefore all these open issues need to be explored before a commercial deployment of such architectures becomes a reality.

REFERENCES

[1] W. E. Stephens, T. R. Joseph and B. U. Chen, "Analog Microwave Fiber Optic Communications Links", *IEEE MTT-S Int'l. Microwave Symposium Digest*, San Francisco, CA, USA, June 1984, pp. 533 – 534.

[2] M. Maier, N. Ghazisaidi and M. Reisslein, "The Audacity of Fiber-Wireless (FiWi) Networks (Invited Paper)," *in Lecture Notes of ICST*, volume 6, pp.16-35: http://dx.doi.org/10.1007/978-3-642-04648-3_2.

[3] K. Tanaka, A. Agata and Y. Horiuchi, "IEEE 802.3av 10G-EPON standardization and its research and development status", *Journal of Lightwave Technology*, vol. 28, no. 4, Feb 2010, pp. 651–661.

[4] ICT Project: SARDANA, Scalable Advanced Ring-based Passive Dense Access Network Architecture SARDANA, *7th Framework Programme* – ICT Project: SARDANA, [Online]. Available: www.ict-sardana.eu [Accessed 01 Nov. 2010].

[5] Gigawam Consortium, GigaWam, Gigawam Site, [Online]. Available: http://www.gigawam.com [Accessed 01 Nov. 2010].

[6] *Information technology–Telecommunications and information exchange between systems–Local and metropolitan area networks–Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 5: Enhancements for Higher Throughput*, IEEE Standard 802.11n-2009.

[7] G. R. Hiertz et al., "IEEE 802.11S: THE WLAN MESH STANDARD", *IEEE Wireless Communications*, vol. 17, no. 1, Feb 2010, pp. 104-111.

[8] ITU-R, ITU global standard for international mobile telecommunications ´IMT-Advanced´, Radiocommunication Sector (ITU-R), [Online]. Available: http://www.itu.int/ITU-R/index.asp?category=information&rlink=imt-advanced&lang=en [Accessed 01 Nov. 2010].

[9] G. Shen, R. S. Tucker and T. Chae, "Fixed Mobile Convergence (FMC) Architectures for Broadband Access: Integration of EPON and WiMAX," *IEEE Communications Magazine*, vol. 45, no. 8, Aug. 2007, pp. 44–50.

[10] S. Sarkar, S. Dixit and B. Mukherjee, "Hybrid Wireless-Optical Broadband-Access Network (WOBAN): A Review of Relevant Challenges", *Journal of Lightwave Technology*, vol. 25, no. 11, Nov 2007, pp. 3329 – 3340.

[11] D. Remondo et al., "Integration of Optical and Wireless Technologies in the Metro-Access: QoS Support and Mobility Aspects", *in Proc. NGI Networks '09*, Aveiro, Portugal, Jul 2009.

[12] N. Ghazisaidi, M. Maier and C. Assi, "Fiber-wireless (FiWi) access networks: A survey", *IEEE Communications Magazine*, vol.47, no.2, pp.160-167, February 2009.