Fiber-Wireless (FiWi) Access Networks: A Survey

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ABSTRACT

This article provides an up-to-date survey of hybrid fiber-wireless (FiWi) access networks that leverage on the respective strengths of optical and wireless technologies and converge them seamlessly. FiWi networks become rapidly mature and give rise to new powerful access network solutions and paradigms. The survey first overviews the state of the art, enabling technologies, and future developments of wireless and optical access networks, respectively, paying particular attention to wireless mesh networks and fiber to the home networks. After briefly reviewing some generic integration approaches of EPON and WiMAX networks, several recently proposed FiWi architectures based on different optical network topologies and WiFi technology are described. Finally, technological challenges toward the realization and commercial adoption of future FiWi access networks are identified.

INTRODUCTION

The ultimate goal of the Internet and communication networks in general is to provide access to information when we need it, where we need it, and in whatever format we need it in. To achieve this goal, wireless and optical technologies play a key role. Wireless and optical access networks can be thought of as complementary. Optical fiber does not go everywhere, but where it does go, it provides a huge amount of available bandwidth. Wireless access networks, on the other hand, potentially go almost everywhere, but provide a highly bandwidth-constrained transmission channel susceptible to a variety of impairments. Clearly, as providers need to satisfy users with continuously increasing bandwidth demands, future broadband access networks must leverage on both technologies and converge them seamlessly, giving rise to *fiber-wireless* (FiWi) access networks.

Passive optical networks (PONs) might be viewed as the final frontier of optical fiber to the home (FTTH) or close to it (FTTX) networks, where they interface with a number of wireless access technologies. One interesting approach to integrate optical fiber networks and wireless networks are so-called radio-over-fiber (RoF) networks. RoF networks are attractive since they provide transparency against modulation technique,s and are able to support various digital formats and wireless standards in a cost-effective manner, for example, wideband code-division multiple access (WCDMA), IEEE 802.11 wireless local area network (WLAN), personal handyphone system (PHS), and Global System for Mobile Communications (GSM) [1]. To realize future multiservice access networks, the seamless integration of RoF systems with existing and emerging optical access networks is important, such as FTTX and wavelength-division multiplexing (WDM) PON networks. RoF networks are also well suited to avoid frequent handovers of fast-moving users in cellular networks. An interesting approach to avoid handovers for train passengers is the use of an optical fiber WDM ring-based RoF network installed along the rail tracks in combination with the moving cell concept, as recently proposed in [2]. The concept of moving cells enables a cell pattern and a train to move along on the same radio frequency during the whole connection in a synchronous fashion without requiring handovers.

In this article we assume that optical fiber paves all the way to and penetrates into the homes of residential and business customers. Arguing that, due to its unique properties, optical fiber is likely to entirely replace copper wires in the near to midterm, we elaborate on the final frontier of optical networks: convergence with their wireless counterparts. Optical and wireless technologies are expected to coexist over the next decades. Future broadband access networks will be bimodal, capitalizing on the respective strengths of both technologies and smartly merging them in order to realize future-proof FiWi networks that strengthen our information society while avoiding its digital divide. By combining the capacity of optical fiber networks with the ubiquity and mobility of wireless networks, FiWi networks form a powerful platform for the support and creation of emerging as well as future unforeseen applications and services (e.g., telepresence). FiWi networks hold great promise to change the way we live and work by replacing commuting with teleworking. This not only provides more time for professional and personal

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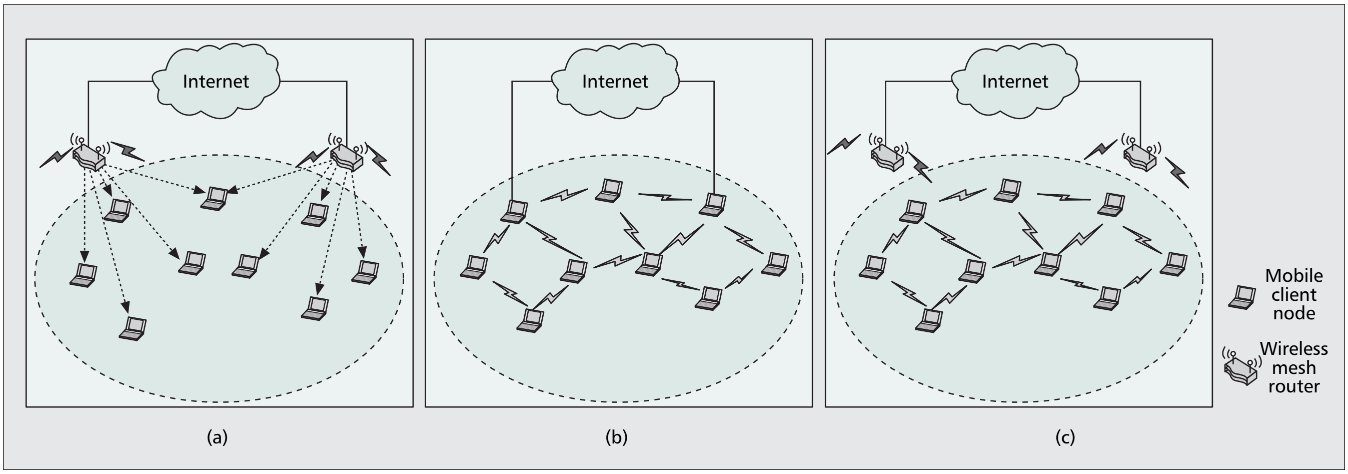


Figure 1. *Wireless mesh networks: a) infrastructure; b) client; c) hybrid.*

activities for corporate and personal benefit, but also helps reduce fuel consumption and protect the environment, issues that are becoming increasingly important in our lives [3].

In this article we provide an up-to-date survey of FiWi access networks. After reviewing state-of-the-art wireless and optical access networks and briefly highlighting future developments in both areas, we focus on enabling technologies and elaborate on emerging FiWi architectures, and also discuss their future challenges. The remainder of the article is structured as follows. The next two sections overview the state of the art of wireless and optical (wired) access networks, respectively. We then describe enabling technologies and various FiWi network architectures. In the following section we address future challenges of emerging FiWi networks. The final section concludes the article.

WIRELESS ACCESS NETWORKS: STATE OF THE ART

WIRELESS MESH NETWORKS

Recent advances in wireless communications technology have led to significant innovations that have enabled cost-effective and flexible wireless Internet access, and provided incentives for building efficient multihop wireless networks. A wireless ad hoc network precludes the use of a wired infrastructure and allows hosts to communicate either directly or indirectly over radio channels without requiring any prior deployment of network infrastructure.

Wireless mesh networks (WMNs), on the other hand, are networks employing multihop communications to forward traffic en route to and from wired Internet entry points [4]. In contrast to conventional WLANs and mobile ad hoc networks (MANETs), WMNs promise greater flexibility, increased reliability, and improved performance. WMNs can be categorized into infrastructure, client, and hybrid WMNs (Fig. 1). A router in an infrastructure WMN has no mobility and performs more functions than a normal wireless router. Among others, a router performs mesh functions (routing and configuration) and acts as a gateway. In a client WMN, clients perform mesh and gateway functions themselves. Efficient routing protocols provide paths through the wireless mesh and react to dynamic changes in the topology, so mesh nodes can communicate with each other even if they are not in direct wireless range. Intermediate nodes on the path forward packets to the final destination. Due to the similarities between WMNs and MANETs, WMNs can apply ad hoc routing protocols (e.g., ad hoc on-demand distance vector [AODV] and dynamic source routing [DSR], among others).

ENABLING TECHNOLOGIES

New technologies and protocols in the physical (PHY) layer, medium access control (MAC) protocols, and routing protocols are required to optimize the performance of WMNs. In the PHY layer, smart antenna, multi-input multi-output (MIMO), ultra wideband (UWB), and multi-channel interface systems are being explored to enhance network capacity and further enable wireless gigabit transmission. Recently, gigabit transmission resulting from a combination of MIMO and orthogonal frequency-division multiplexing (OFDM) has been demonstrated. MAC protocols based on distributed time-division multiple access (TDMA) and CDMA are expected to improve the bandwidth efficiency of carrier sense multiple access with collision avoidance (CSMA/CA) protocols [4].

Currently, IEEE 802.11 a/b/g (WiFi) technologies are widely exploited in commercial products and academic research of WMNs due to their low cost, technological maturity, and high product penetration [5]. However, since these protocols were originally designed for WLANs, they clearly are not optimized for WMNs. Proprietary wireless technologies and WiMAX have been proposed. Unlike WiFi, IEEE 802.16 allows for point-to-multipoint wireless connections with a transmission rate of 75 Mb/s and can be used for longer distances.

Additionally, orthogonal frequency-divisiom multiple access (OFDMA) and smart antenna technologies extend the scalability of WiMAX. These technologies are exploited to enhance the capacity, reliability, and mobility of WMNs.

Optical networks lend themselves well to offloading electronic equipment by means of optical bypassing as well as reducing their complexity, footprint, and power consumption significantly while providing optical transparency against modulation format, bit rate, and protocol.

Ultra-high-bandwidth standards such as IEEE 802.16m, which aims to provide 1 Gb/s and 100 Mb/s shared bandwidth, can be employed to further enhance the bandwidth and mobility of WMNs. Since packets are routed among mesh routers in the presence of interference, shadowing, and fading, a cross-layer design is required to optimize the routing in WMNs. For instance, DSR uses link quality source routing (LQSR) to select a routing path according to link quality metrics. LQSR includes three performance metrics: per-hop packet pair, per-hop round-trip time (RTT), and expected transmission count (ETX). ETX shows the best performance in networks with fixed nodes, while minimum hop count shows good performance in networks with mobile nodes.

FUTURE DEVELOPMENTS

Given the increased demand for mesh networks, a task group was formed in 2004 to define the Extended Service Set (ESS) mesh networking standard; its goal is the development of a flexible and extensible standard for WMNs based on IEEE 802.11. The IEEE 802.11s amendment can be split up into four major parts: multihop routing, MAC enhancements, security, and general topics. It also defines a new mesh data frame format that can be used for transmitting data within the WMN. Traffic in mesh networks is predominantly forwarded to and from wireline gateway nodes forming a logical tree structure. The 802.11s defines a default mandatory routing protocol (Hybrid Wireless Mesh Protocol [HWMP]) that uses hierarchical routing to exploit this tree-like logical structure and on demand routing protocols to address mobility; the on demand routing protocol is based on AODV, which uses a simple hop count routing metric. Alternatively, the standard allows vendors to operate using alternate protocols, one of which is described in the draft (Radio Aware Optimized Link State Routing [RA-OLSR]). RA-OLSR uses multipoint relays, a subset of nodes that flood a radio-aware link metric, thereby reducing control overhead on the routing protocol.

Other interesting developments are concerned with the integration of different access technologies; for instance, the authors of [6] presented an approach for integrating WiMAX and WiFi technologies, and discussed several issues pertaining to protocol adaptation and QoS support.

OPTICAL ACCESS NETWORKS: STATE OF THE ART

Optical fiber provides unprecedented bandwidth potential far in excess of the wireless and any other known transmission medium. A single strand of fiber offers a total bandwidth of 25,000 GHz. More important, optical networks lend themselves well to offloading electronic equipment by means of optical bypassing as well as reducing their complexity, footprint, and power consumption significantly while providing optical transparency against modulation format, bit rate, and protocol.

FTTX NETWORKS

FTTX networks are poised to become the next major success story for optical fiber communications. Not only must future FTTX access networks unleash the economic potential and societal benefit by opening up the first/last mile bandwidth bottleneck between bandwidth-hungry end users and high-speed backbone networks, but also enable the support of a wide range of new and emerging services and applications, such as triple play, video on demand, point-to-point (P2P) audio/video file sharing and streaming, multichannel HDTV, multimedia/multiparty online gaming, and telecommuting. Due to their longevity, low attenuation, and huge bandwidth, PONs are widely deployed to realize cost-effective FTTX access networks [7].

PONS

Typically, PONs are time-division multiplexing (TDM) single-channel systems, where the fiber infrastructure carries a single upstream wavelength channel (from subscribers to a central office) and a single downstream wavelength channel (from a central office to subscribers). IEEE 802.3ah Ethernet PON (EPON) with a symmetric line rate of 1.25 Gb/s, and International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) G.984 Gigabit PON (GPON) with an upstream line rate of 1.244 Gb/s and a downstream line rate of 2.488 Gb/s represent current state-of-the-art commercially available and widely deployed TDM PON access networks, but standardization efforts have already been initiated in the IEEE 802.3av Task Force to specify 10 Gb/s EPON. GPON offers strong operation, administration, maintenance, and provisioning (OAMP) capabilities, and provides security at the protocol level for downstream traffic by means of encryption using Advanced Encryption Standards. Furthermore, GPON efficiently supports traffic mixes consisting not only of asynchronous transfer mode (ATM) cells but also TDM (voice) and variable-size packets by using the GPON encapsulation method (GEM). EPON aims at converging the low-cost equipment and simplicity of Ethernet and the low-cost infrastructure of PONs. Security and OAMP are not specified in the EPON standard IEEE 802.3ah, but may be implemented using the data over cable service interface specification (DOCSIS) OAMP service layer on top of the MAC and PHY layers of EPON. Given the fact that 95 percent of LANs use Ethernet, and most applications and services (e.g., video) are moving toward Ethernet, in conjunction with Ethernet's low cost and simplicity, EPON is expected to increasingly become the norm.

Both GPON and EPON are commonly perceived to carry a single wavelength channel in each direction. The majority of real-world PON deployments, however, use an additional downstream wavelength channel for video distribution according to the wavelength allocation in ITU-T Recommendation G.983.3, which specifies a so-called enhancement band from 1539 to 1565 nm plus an L-band reserved for future use. The enhancement band and L-band can be used to

Features	FSO	RoF
Connectivity	Point-to-point	Point-to-point and point-to-multipoint
Transmission mode	Full duplex	Full duplex
Scalability	High in terms of bandwidth Low in terms of user and service	Low in terms of bandwidth High in terms of user and service
Availability	Low in fog High in rain	High in fog Low in rain
Interference	Background sunlight	Electromagnetic signals
Spectrum licence	Not required	Required

Table 1. *Comparison between wireless segments of FSO and RoF.*

FSO is a type of direct line-of-sight (LOS) optical communications that provides point-to-point connections by modulating visible or infrared (IR) beams [9]. It offers high bandwidth and reliable communications over short distances.

enable additional services such as overlay of multiple PONs on a single fiber infrastructure or optical time domain reflectometry (OTDR) for testing and troubleshooting.

FUTURE DEVELOPMENTS

Adding the wavelength dimension to conventional TDM PONs leads to WDM PONs, which have several advantages. Among others, the wavelength dimension may be exploited to:

- Increase network capacity
- Improve network scalability by accommodating more end users
- Separate services
- Separate service providers [7]

An interesting approach to increasing split ratio (i.e., number of subscribers) and range is the so-called long-reach PON (LR-PON), which is currently receiving considerable attention from network operators in an attempt to optically bypass central offices and consolidate optical metro and access networks, resulting in major cost savings and simplified network operation. LR-PONs can also be interesting for new operators wishing only to connect the major geographically distributed business clients.

Most of the reported studies on advanced PON architectures have considered standalone PON access networks, with a particular focus on the design of dynamic bandwidth allocation (DBA) algorithms for quality of service (QoS) support and QoS protection by means of admission control [8].

FIWI NETWORKS

ENABLING TECHNOLOGIES

Currently, there are two technologies used to implement fiber-wireless (FiWi) networks:

- Free space optical (FSO), also known as optical wireless (OW)
- Radio over fiber (RoF)

FSO is a type of direct line-of-sight (LOS) optical communications that provides point-to-point connections by modulating visible or infrared (IR) beams [9]. It offers high bandwidth and reliable communications over short distances. The transmission carrier is generated by deploying either a high-power light emitting diode (LED) or a laser diode, while the receiver may deploy a simple photo detector. Current FSO systems operate in full-duplex mode at a transmission rate ranging from 100 Mb/s to 2.5 Gb/s, depending largely on weather conditions. Given a clear LOS between source and destination and enough transmitter power, FSO communications can work over distances of several kilometers. At both source and destination, optical fiber may be used to build high-speed LANs, such as Gigabit Ethernet (GbE).

RoF, on the other hand, allows an analog optical link to transmit a modulated radio frequency (RF) signal. There are different techniques available to realize RoF networks. Typically, an RoF transmitter deploys a Mach-Zehnder intensity (MZI) modulator in conjunction with an oscillator that generates the required optical carrier frequency, followed by an Erbium doped fiber amplifier (EDFA) in order to increase the transmission range. RoF networks provide both P2P and point-to-multipoint connections. Recently, a full-duplex RoF system providing 2.5 Gb/s data transmission over 40 km with less than 2 dB power attenuation was successfully demonstrated using the millimeter-wave band [10]. There are many cost-efficient optical approaches to mixing and upconverting millimeter wave signals.

Table 1 summarizes and compares the salient features of both enabling technologies of FiWi networks.

ARCHITECTURES

We present in this section available architectures for enabling FiWi integration. For instance, the integration of EPON and WiMAX access networks can be done in several ways; according to [11], the following four architectures can be used.

Independent Architecture — In this approach WiMAX base stations serving mobile client nodes are attached to an optical network unit (ONU) just like any other wired subscriber node, whereby an ONU denotes the EPON customer premises equipment. WiMAX and EPON networks are connected via a common standardized interface (e.g., Ethernet) and operate independent of each other.

Hybrid Architecture — This approach introduces an ONU-base station (ONU-BS) that integrates the EPON ONU and WiMAX BS in both hardware and software. The integrated ONU-BS controls the dynamic bandwidth allocation of both the ONU and BS.

Unified Connection-Oriented Architecture — Similar to the hybrid architecture, this approach deploys an integrated ONU-BS. But instead of carrying Ethernet frames, WiMAX MAC protocol data units (PDUs) containing multiple encapsulated Ethernet frames are used. By carrying WiMAX MAC PDUs, the unified architecture can be run like a WiMAX network with the ability to grant bandwidth finely using WiMAX's connection-oriented rather than EPON's queue-oriented bandwidth allocation.

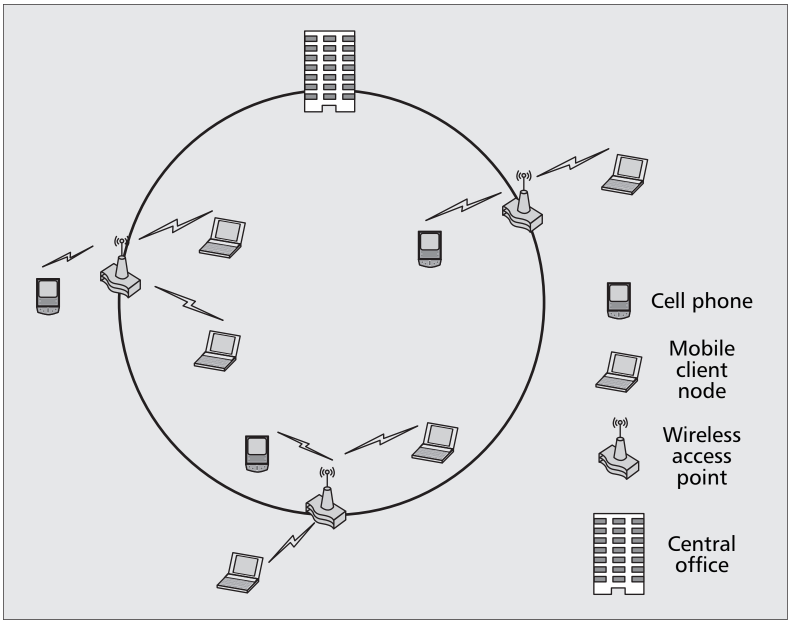


Figure 2. *Optical unidirectional fiber ring interconnecting WiFi-based wireless access points.*

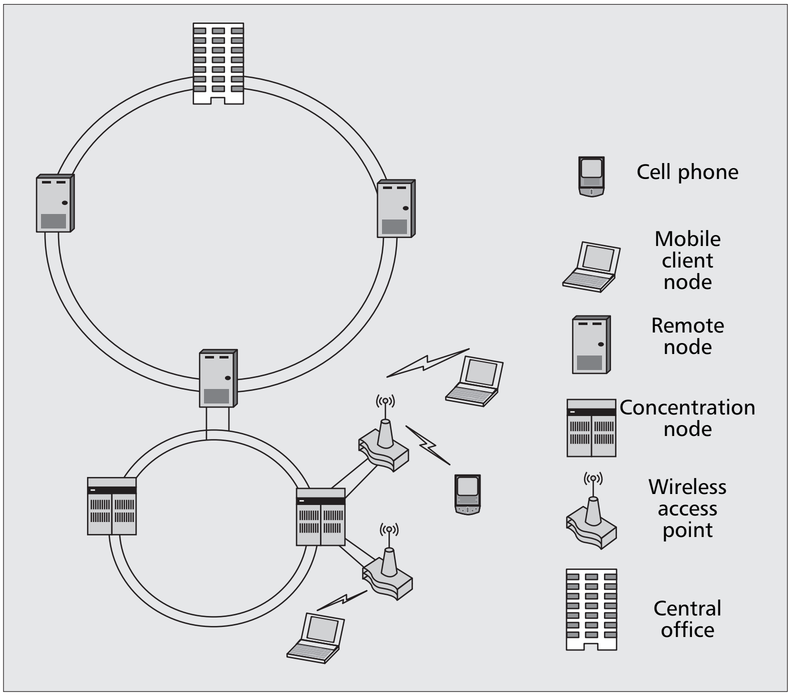


Figure 3. *Optical interconnected bidirectional fiber rings integrated with WiFi-based wireless access points.*

Microwave-over-Fiber Architecture — In this approach the WiMAX signal is modulated on a wireless carrier frequency, and is then multiplexed and modulated together with the baseband EPON signal onto a common optical frequency (wavelength) at the ONU-BS. The central node consists of a conventional EPON optical line terminal (OLT) and a central WiMAX BS, called a macro-BS. The OLT processes the baseband EPON signal, while the macro-BS processes data packets originating from multiple WiMAX BS units.

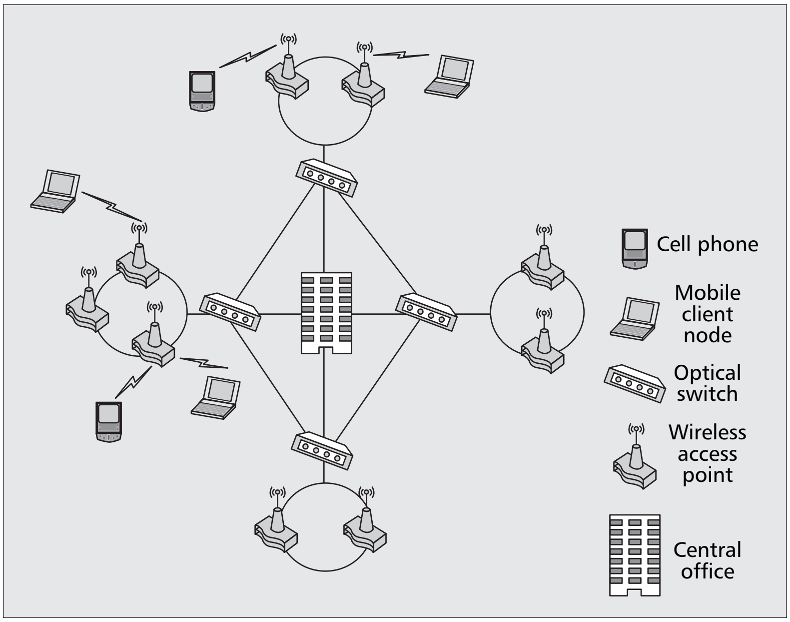
Besides the aforementioned generic integration approaches of EPON and WiMAX networks, several other FiWi architectures based on WiFi technology have been studied, as described in the following.

The network shown in Fig. 2 interconnects the central office (CO) with multiple WiFi-based wireless access points (WAPs) by means of an optical unidirectional fiber ring [12]. The CO is responsible for managing the transmission of information between mobile client nodes (MCNs) and their associated WAPs as well as acting as a gateway to other networks. Each WAP provides wireless access to MCNs within its range. All MCNs take part in the topology discovery, whereby each MCN periodically sends the information about the beacon power received from its neighbors to its associated WAP. In doing so, WAPs are able to estimate the distances between MCNs and compute routes. Multihop relaying is used to extend the range. To enhance the reliability of the wireless link, the CO sends information to two different WAPs (path diversity). The proposed implementation can support advanced path diversity techniques that use a combination of transmission via several WAPs and multihop relaying (e.g., cooperative diversity or multihop diversity). Consequently, the CO must be able to assign channels quickly and efficiently by using one or more wavelength channels on the fiber ring to accommodate multiple services such as WLAN and cellular radio network.

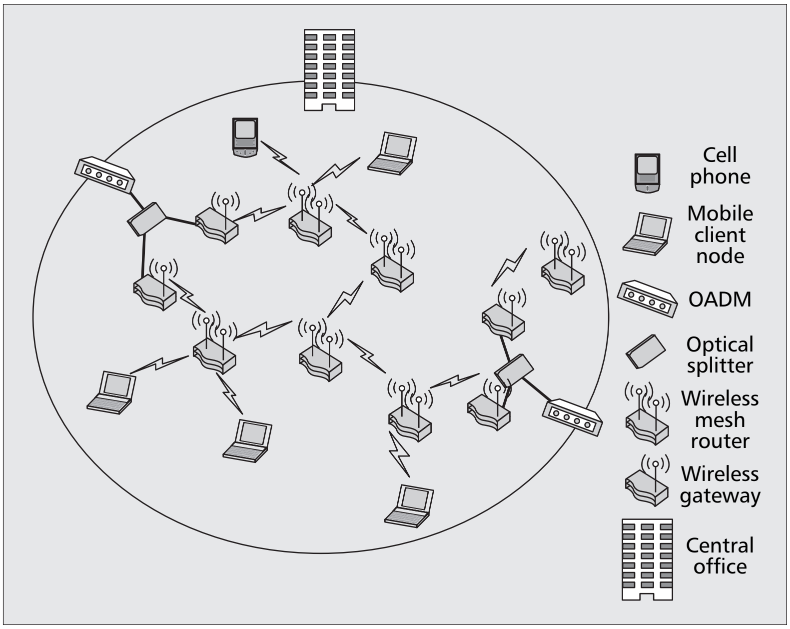
Figure 3 shows a two-level bidirectional path-protected ring (BPR) architecture for dense WDM (DWDM)/subcarrier multiplexing (SCM) broadband FiWi networks [13]. In this architecture the CO interconnects remote nodes (RNs) via a dual-fiber ring. Each RN cascades WAPs through concentration nodes (CNs), where each WAP offers services to MCNs. For protection, the CO is equipped with two sets of devices (normal and standby). Each RN consists of a protection unit and a bidirectional wavelength add-drop multiplexer based on a multilayer dielectric interference filter. Each CN contains a protection unit. The WAP comprises an optical transceiver, a protection unit, up/down RF converters, and a sleeve antenna. Each WAP provides channel bandwidth of at least 5 MHz and covers up to 16 MCNs by means of frequency-division multiplexing (FDM). Under normal operating conditions, the CO transmits downstream signals in the counter-clockwise direction via RNs and CNs to the WAPs. If a fiber cut occurs between two RNs or between two CNs, their associated controllers detect the failure by monitoring the received optical signal and then switch to the clockwise protection ring. If a failure happens at a WAP, the retransmitted signals are protection switched through other optical paths by throwing an optical switch inside the affected WAP. This architecture provides high reliability, flexibility, capacity, and self-healing properties.

Figure 4 depicts a hybrid FiWi architecture that combines optical star and ring networks [14]. Each fiber ring accommodates several WiFi-based WAPs, and is connected to the CO and two neighboring fiber rings via optical switches. The optical switches have full wavelength conversion capability, and interconnect the WAPs and CO by means of shared P2P lightpaths. The network is periodically monitored during prespecified intervals. At the end of each interval, the lightpaths may be dynamically reconfigured in response to varying traffic demands. When traffic increases and the utilization of the established lightpaths is low, the load on the existing lightpaths is increased by means of load balancing. Otherwise, if the established lightpaths are heavily loaded, new lightpaths need to be set up, provided enough capacity is available on the fiber links. In the event of one or more link failures, the affected lightpaths are dynamically reconfigured using the redundant fiber paths of the architecture.

The FiWi network proposed in [15] consists of an optical WDM backhaul ring with multiple single-channel or multichannel PONs attached to it, as shown in Fig. 5. More precisely, an optical add-drop multiplexer (OADM) is used to connect the OLT of each PON to the WDM ring. Wireless gateways are used to bridge PONs and WMNs. In the downstream direction, data packets are routed from the CO to the wireless gateways through the optical backhaul and then forwarded to the MCNs by wireless mesh routers. In the upstream direction, wireless mesh routers forward data packets to one of the wireless gateways, where they are then transmitted to the CO on one of the wavelength channels of the optical backhaul WDM ring, as each PON operates on a separate dynamically allocated wavelength channel. Since the optical backhaul and WMN use different technologies, an interface is defined between each ONU and the corresponding wireless gateway in order to monitor the WMN and perform route computation taking the state of wireless links and average traffic rates into account. When the traffic demands surpass the available PON capacity, some of the TDM PONs may be upgraded to WDM PONs. If some PONs are heavily loaded and others have less traffic, some heavily loaded ONUs may be assigned to a lightly loaded PON by tuning their optical transceivers to the wavelength assigned to the lightly loaded PON. This architecture provides cost effectiveness, bandwidth efficiency, wide coverage, high flexibility, and scalability. In addition, the reconfigurable TDM/WDM optical backhaul helps reduce network congestion and average packet latency by means of load balancing. Moreover, the dynamic allocation of radio resources enables cost-effective and simple handovers.



■ **Figure 4.** *Optical hybrid star-ring network integrated with WiFi-based wireless access points.*



■ **Figure 5.** *Optical unidirectional WDM ring interconnecting multiple PONs integrated with a WiFi-based wireless mesh network.*

FUTURE CHALLENGES

We have seen that FiWi networks can be realized by deploying different architectures and several technologies. Toward commercial adoption, FiWi access networks still face a number of technological challenges. One of the most critical challenges is to determine a feasible, scalable, and resilient architecture along with the corresponding enabling technologies. As discussed earlier, future broadband access networks will undoubtedly be a combination of first/last mile optical fiber access solutions (i.e., FTTX) and heterogeneous broadband wireless networks providing connectivity to end users. One first challenge is to seamlessly integrate these technologies; while FTTX networks provide TDMA to wired ONUs, mobile client nodes in a WMN access the medium through enhanced distributed channel access (EDCA) and multihop routing used to forward their packets to wireless mesh gateways.

By seamlessly converging optical and wireless access technologies, hybrid FiWi access networks hold great promise to support a plethora of future and emerging broadband services and applications on the same infrastructure.

New approaches to exploit the huge bandwidth available in optical access networks for offloading bandwidth-limited wireless networks should be studied in greater detail. The design and evaluation of powerful load balancing and reconfiguration techniques to improve the bandwidth efficiency of future FiWi networks is another interesting research avenue, including reconfiguration techniques for unpredictable traffic. Routing in WMNs remains a critical issue, and designing efficient routing protocols that are aware of the bandwidth allocation on PON is more challenging; routing algorithms that exploit this large bandwidth potential to offer fair access to WMN nodes as well as load balancing across the mesh links are key for future FiWi networks. Additionally, these current access networks are designed to carry traffic with various QoS requirements. Various QoS bandwidth allocation algorithms for PONs have emerged; however, designing QoS-aware routing protocols in WMNs is still an open issue and is not addressed within the 802.11s standard. In general, applications have different QoS requirements. Research on powerful end-to-end resource allocation techniques in FiWi networks is necessary.

Resiliency against failures is another challenge of future FiWi networks. FiWi networks should allow WMN gateways to interconnect with the optical backhaul through multiple points in order to enable multipath routing and improve their survivability. Additionally, the optical backhaul should implement appropriate protection switching functions to deal with network element failures rapidly.

The 802.11s standard currently defines a new frame format for transmitting traffic over the WMN. However, most of today's deployed PON systems are based on EPON or BPON/GPON. Therefore, interfaces are needed to allow for protocol adaptation and enable network interoperability.

Finally, implementation simplicity will be key to the commercial success of FiWi networks. Reducing the installation and protection costs by means of transferring expensive devices and complex functions to the central office appears to be a promising approach to building cost-effective FiWi networks. In particular, cost-efficient and feasible modulation formats for optical/RF signal conversion are needed. Despite recent developments in RoF networks, more research on physical layer related issues is necessary due to the high atmospheric absorption in high-frequency bands such as the millimeter-wave band.

CONCLUSIONS

By seamlessly converging optical and wireless access technologies, hybrid FiWi access networks hold great promise to support a plethora of future and emerging broadband services and applications on the same infrastructure. We have observed that research and development of future FiWi network architectures and protocols have made significant progress, but many open issues mostly related to the design of low-cost components, integrated routing, end-to-end service differentiation, and resiliency must be solved in order to render FiWi access solutions commercially viable. By simultaneously providing wired and wireless services over the same infrastructure, FiWi networks are able to consolidate (optical) wired and wireless access networks that are usually run independent of each other, thus potentially leading to major cost savings. An interesting future research avenue would be the techno-economic comparison of different FiWi network architectures.

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BIOGRAPHIES

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MARTIN MAIER (maier@ieee.org) was educated at the Technical University of Berlin, Germany, and received M.Sc. and Ph.D. degrees, both with distinction (summa cum laude), in 1998 and 2003, respectively. In the summer of 2003 he was a post-doctoral fellow at the Massachusetts Institute of Technology (MIT), Cambridge. He is an associate professor at Institut National de la Recherche Scientifique (INRS), Montreal, Canada. He was a visiting professor at Stanford University, California, October 2006 through March 2007. He is the founder and creative director of the Optical Zeitgeist Laboratory (http://www.zeitgeistlab.ca). His research aims at providing insights into technologies, protocols, and algorithms shaping the future of optical networks and their seamless integration with broadband wireless access networks. He is the author of the books *Optical Switching Networks* (Cambridge University Press, 2008) and *Metropolitan Area WDM Networks: An AWG Based Approach* (Kluwer, 2003).