The Audacity of Fiber-Wireless (FiWi) Networks
(Invited Paper)

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Abstract. A plethora of enabling optical and wireless technologies have been emerging that can be used to build future-proof bimodal fiber-wireless (FiWi) broadband access networks. After overviewing key enabling radio-over-fiber (RoF) and radio-and-fiber (R&F) technologies and briefly surveying the state of the art of FiWi networks, we introduce an Ethernet-based access-metro FiWi network, called SuperMAN, that integrates next-generation WiFi and WiMAX networks with WDM-enhanced EPON and RPR networks. Throughout the paper we pay close attention to the technical challenges and opportunities of FiWi networks, but also elaborate on their societal benefits and potential to shift the current research focus from optical-wireless networking to the exploitation of personal and in-home computing facilities to create new unforeseen services and applications as we are about to enter the Petabyte age.

Keywords: EPON, FiWi, FTTH, MAC, optical-wireless integration, path selection, QoS, R&F, RoF, RPR, WiFi, WiMAX, WMN.

1 Introduction

We are currently witnessing a strong worldwide push toward bringing optical fiber closer to individual homes and businesses, leading to fiber to the home/fiber to the premises (FTTH/FTTP) networks [1]. In FTTx networks, fiber is brought close or all the way to the end user, whereby x denotes the discontinuity between optical fiber and some other, either wired or wireless, transmission medium. For instance, cable operators typically deploy hybrid fiber coax (HFC) networks where fiber is used to build the feeder network while the distribution network is realized with coax cables. Another good example for wired fiber-copper access networks are hybrid fiber-twisted pair networks which are widely deployed by telephone companies to realize different variants of digital subscriber line (DSL) broadband access solutions.

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From a capacity point of view, one might seriously argue that there is no techno-economic need and justification to replace hybrid fiber-twisted pair based DSL networks with all-optical solutions, e.g., passive optical networks (PONs). According to [2], the so-called Copper-PON (CuPON) multidropping DSL architecture is able to provide 50 Gb/s of shared bandwidth in each direction on existing twisted pair of copper telephone lines through exploitation of all modes of crosstalk. Thus, CuPON is able to offer much higher data rates than state-of-the-art standardized access network solutions, e.g., IEEE 802.3ah Ethernet PON (EPON) and ITU-T G.984 Gigabit PON (GPON), without requiring any costly replacement of widely installed twisted pairs by fiber. Note, however, that the speed of CuPON is higher than that of current fiber PONs not because copper has a wider bandwidth than fiber, but because current fiber PONs do not use their extra bandwidth. In fact, optical fiber provides an unprecedented bandwidth potential that is far in excess of any other known transmission medium. A single strand of fiber offers a total bandwidth of 25 000 GHz. To put this potential into perspective, it is worthwhile to note that the total bandwidth of radio on the planet Earth is not more than 25 GHz [3]. Beside huge bandwidth, optical fiber has some further advantageous properties such as low attenuation, longevity, and low maintenance costs which will eventually render fiber the medium of choice in wired first/last mile access networks. This trend can be observed in most of today's greenfield deployments where fiber rather than copper cables are installed for broadband access. On the other hand, in brownfield deployments it is important that installation costs, which largely contribute to overall costs of access networks, be reduced. A promising example for cutting installation costs is NTT's do-it-yourself (DIY) installation of FTTH optical network units (ONUs) deploying a user-friendly hole-assisted fiber that exhibits negligible loss increase and sufficient reliability, even when it is bent at right angles, clinched, or knotted, and can be mass produced economically [4]. Another interesting enabling technology is the so-called plastic optical fiber (POF) which is well suited for simple wiring of low-cost optical home networks. POF provides consumers with user-friendly terminations, easy installation, and tolerance of dirty connections. Furthermore, POF's resistance to bending is comparable to that of twisted pair of copper telephone lines. An interesting application of POF-based networks is the concept of "Fiber to the Display" where POFs are directly connected to a large flat panel display to enable transmission rates of several Gb/s in support of telemedicine or the emerging digital cinema standard for next-generation cinema [5].

FTTH networks are expected to become the next major success story for optical communications systems [6]. Future FTTH networks will not only enable the support of a wide range of new and emerging services and applications but also unleash their economic potential and societal benefits by opening up the first/last mile bandwidth bottleneck between bandwidth-hungry end users and high-speed backbone networks [7]. In this paper, we assume that optical fiber paves all the way to and penetrates into the home 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 mid term, we will elaborate on the final frontier of optical networks, namely, the convergence with their wireless counterparts. Optical and wireless technologies can be thought of as quite complementary and will expectedly 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 fiber-wireless (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 activities for corporate and our own personal benefit, but also helps reduce fuel consumption and protect the environment, issues that are becoming increasingly important in our lives.

The remainder of the paper is structured as follows. In Section 2, we set the stage by briefly reviewing radio-over-fiber (RoF) networks, a previously studied approach to integrate optical fiber networks and wireless networks, and explain their difference to so-called radio-and-fiber (R&F) networks. Section 3 elaborates on enabling technologies and the state of the art of FiWi networks. In Section 4, we introduce our proposal for future FiWi networks. Section 5 concludes the paper.

2 RoF vs. R&F Networks

RoF networks have been studied for many years as an approach to integrate optical fiber and wireless networks. In RoF networks, radiofrequencies (RFs) are carried over optical fiber links between a central station and multiple low-cost remote antenna units (RAUs) in support of a variety of wireless applications. For instance, a distributed antenna system connected to the base station of a microcellular radio system via optical fibers was proposed in [8]. To efficiently support time-varying traffic between the central station and its attached base stations, a centralized dynamic channel assignment method is applied at the central station of the proposed fiber optic microcellular radio system. To avoid having to equip each radio port in a fiber optic microcellular radio network with a laser and its associated circuit to control the laser parameters such as temperature, output power, and linearity, a cost-effective radio port architecture deploying remote modulation can be used [9].

Apart from realizing low-cost microcellular radio networks, optical fibers can also be used to support a wide variety of other radio signals. RoF networks are attractive since they provide transparency against modulation techniques and are able to support various digital formats and wireless standards in a cost-effective manner. It was experimentally demonstrated in [10] that RoF networks are well suited to simultaneously transmit wideband code division multiple access (WCDMA), IEEE 802.11a/g wireless local area network (WLAN), personal handyphone system (PHS), and global system for mobile communications (GSM) signals. Fig. 1 illustrates the method investigated in [10] for two different radio

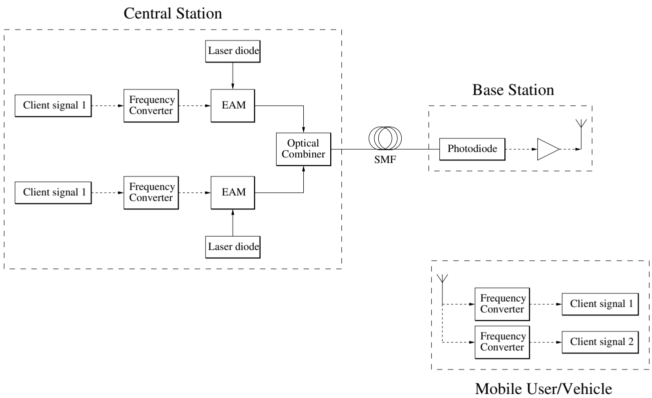

Fig. 1. Radio-over-SMF network downlink using EAMs for different radio client signals [10]

client signals transmitted by the central station on a single-mode fiber (SMF) downlink to a base station and onward to a mobile user or vehicle. At the central station, both radio client signals are first upconverted to a higher frequency by using a frequency converter. Then the two RF signals go into two different electroabsorption modulators (EAMs) and modulate the optical carrier wavelength emitted by two separate laser diodes. An optical combiner combines the two optical signals onto the SMF downlink. At the base station, a photodiode converts the incoming optical signal to the electrical domain and radiates the amplified signal through an antenna to a mobile user or vehicle which uses two separate frequency converters to retrieve the two different radio client signals.

While SMFs are typically found in outdoor optical networks, many buildings have preinstalled multimode fiber (MMF) cables. Cost-effective multimode fiber (MMF)-based networks can be realized by deploying low-cost vertical cavity surface emitting lasers (VCSELs). In [11], different kinds of MMF in conjunction with commercial off-the-shelf (COTS) components were experimentally tested to demonstrate the feasibility of indoor radio-over-MMF networks for the in-building coverage of second-generation (GSM) and third-generation cellular radio networks [universal mobile telecommunications system (UMTS)] as well as IEEE 802.11a/b/g WLAN and digital enhanced cordless telecommunication packet radio service (DECT PRS).

To realize future multiservice access networks, it is important to integrate RoF systems with existing optical access networks. In [12], a novel approach for simultaneous modulation and transmission of both RoF RF and FTTH baseband signals using a single external integrated modulator was experimentally demonstrated, as shown in Fig. 2. The external integrated modulator consists of three different Mach-Zehnder modulators (MZMs) 1, 2, and 3. MZM 1 and MZM 2 are embedded in the two arms of MZM 3. The RoF RF and FTTH baseband signals independently modulate the optical carrier generated by a common laser diode by using MZM 1 and MZM 2, respectively. Subsequently, the optical wireless RF and wired-line baseband signals are combined at MZM 3. After propagation over

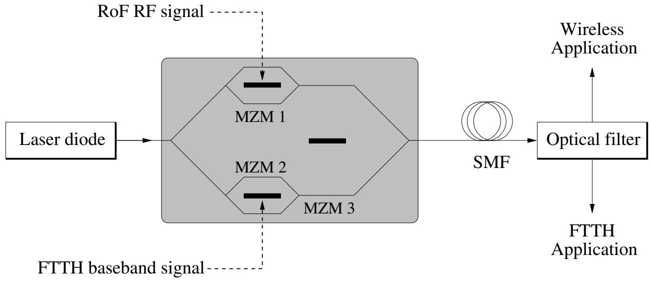

Fig. 2. Simultaneous modulation and transmission of FTTH baseband signal and RoF RF signal using an external integrated modulator consisting of three Mach-Zehnder modulators (MZMs) [12]

an SMF downlink, an optical filter (e.g., fiber grating) is used to separate the two signals and forward them to the wireless and FTTH application, respectively. It was experimentally demonstrated that a 1.25 Gb/s baseband signal and a 20-GHz 622 Mb/s RF signal can be simultaneously modulated and transmitted over 50 km standard SMF with acceptable performance penalties.

The aforementioned research projects successfully demonstrated the feasibility and maturity of low-cost multiservice RoF networks. Their focus was on the investigation of RoF transmission characteristics and modulation techniques, considering primarily physical layer related performance metrics, e.g., power penalty, error vector magnitude (EVM), and bit error rate (BER) measurements. It was shown that RoF networks can have an optical fiber range of up to 50 km. However, inserting an optical distribution system in wireless networks may have a major impact on the performance of medium access control (MAC) protocols [13]. The additional propagation delay may exceed certain timeouts of wireless MAC protocols, resulting in a deteriorated network performance. More precisely, MAC protocols based on centralized polling and scheduling, e.g., IEEE 802.16 WiMAX, are less affected by increased propagation delays due to their ability to take longer walk times between central station and wireless subscriber stations into account by means of interleaved polling and scheduling of upstream transmissions originating from different subscriber stations. However, in distributed MAC protocols, e.g., the widely deployed distributed coordination function (DCF) in IEEE 802.11a/b/g WLANs, the additional propagation delay between wireless stations and access point poses severe challenges. To see this, note that in WLANs a source station starts a timer after each frame transmission and waits for the acknowledgment (ACK) from the destination station. By default the ACK timeout value is set to 9 μs and 20 μs in 802.11a/g and 802.11b WLAN networks, respectively. If the source station does not receive the ACK before the ACK timeout it will resend the frame for a certain number of retransmission attempts. Clearly, one solution to compensate for the additional fiber propagation delay is to increase the ACK timeout. Note, however, that in DCF the ACK timeout must not exceed the DCF interframe space (DIFS), which prevents other stations from accessing the wireless medium and thus avoiding collision with the ACK frame (in IEEE 802.11 WLAN specifications DIFS is set to 50 μs). Due to the ACK timeout, optical fiber can deployed in WLAN-based RoF networks only up to a maximum length. For instance, it was shown in [14] that in a standard 802.11b WLAN network the fiber length must be less than 1948 m to ensure the proper operation of DCF. In addition, it was shown that there is a trade-off between fiber length and network throughput. As more fiber is deployed the network throughput decreases gradually.

The aforementioned limitations of WLAN-based RoF networks can be avoided in so-called radio-and-fiber (R&F) networks [15]. While RoF networks use optical fiber as an analog transmission medium between a central control station and one or more RAUs with the central station being in charge of controlling access to both optical and wireless media, in R&F networks access to the optical and wireless media is controlled separately from each other by using in general two different MAC protocols in the optical and wireless media, with protocol translation taking place at their interface. As a consequence, wireless MAC frames do not have to travel along the optical fiber to be processed at the central control station, but simply traverse their associated access point and remain in the WLAN. In WLAN-based R&F networks, access control is done locally inside the WLAN without involving any central control station, thus avoiding the negative impact of fiber propagation delay on the network throughput. R&F networks are well suited to build WLAN-based FiWi networks of extended coverage without imposing stringent limits on the size of the optical backhaul, as opposed to RoF networks that limit the length of deployed fibers to a couple of kilometers. Recall that this holds only for distributed MAC protocols such as DCF, but not for MAC protocols that deploy centralized polling and scheduling, e.g., WiMAX.

3 FiWi Networks

Both RoF and R&F technologies can be found in FiWi networks. In this section, we discuss enabling technologies in greater detail and elaborate on the state of the art of FiWi networks.

3.1 Enabling Technologies

RoF Technologies. Several RoF technologies have been emerging for the realization of low-cost FiWi networks. In the following, we briefly summarize some of the key enabling RoF technologies. For further details and a technically more profound discussion, we refer the interested reader to [16].

Optical RF Generation. To avoid the electronic bottleneck, the generation of RF signals is best done optically. The following novel optical RF generation techniques were experimentally studied and demonstrated in [16]:

- FWM in HNL-DSF: Four-wave mixing (FWM) in a highly nonlinear dispersion-shifted fiber (HNL-DSF) can be used to realize simultaneous all-optical up-conversion of multiple wavelength channels by using optical carrier suppression (OCS) techniques. FWM is transparent to the bit rate and

modulation format which may be different on each wavelength. Due to the ultrafast response of HNL-DSF, Terahertz optical RF generation is possible.
- XPM in HNL-DSF: Cross-phase modulation (XPM) in a nonlinear optical loop mirror (NOLM) in conjunction with straight pass in HNL-DSF enables the all-optical up-conversion of multiple wavelength channels without any interference- and saturation-effect limitation.
- XAM in EAM: All-optical wavelength up-conversion by means of cross-absorption modulation (XAM) in an electroabsorption modulator (EAM) has several advantages such as low power consumption, compact size, polarization insensitivity, and easy integration with other devices.
- External IM: External intensity modulation (IM) is another approach for optical RF generation, deploying one of three following modulation schemes: double-sideband (DSB), single-sideband (SSB), and OCS.
- External PM: Instead of external IM, external phase modulation (PM) can be used for optical RF generation.

According to [16], external intensity and phase modulation schemes are the most practical solutions for all-optical RF generation due to their low cost, simplicity, and long-distance transmission performance.

Remote Modulation. An interesting approach to build low-cost FiWi networks is the use of a single light source at the central office (CO) to generate a downlink wavelength that is reused at RAUs for upstream transmission by means of remote modulation, thereby avoiding the need for an additional light source at each RAU. The following remodulation schemes were experimentally studied in [16]:

- DPSK for Downstream/OOK for Upstream: PM is deployed to generate a differential phase-shift-keyed (DPSK) optical downstream signal. The DPSK is up-converted through OCS modulation. An optical splitter is used at each RAU to divide the arriving optical signal into two parts. One part is demodulated by a Mach-Zehnder interferometer and is subsequently detected by a photodetector. The other part is on-off-keyed (OOK) remodulated with upstream data using a Mach-Zehnder modulator and is sent to the CO.
- OCS for Downstream/Reuse for Upstream: At the CO, an optical carrier is split prior to optical RF generation by means of OCS and is then combined with the RF signal and sent downstream. Each RAU utilizes a fiber Bragg grating (FBG) to reflect the optical carrier while letting the RF signal pass to a photodetector. The reflected optical carrier is remodulated with upstream data and is then sent back to the CO.
- PM for Downstream/Directly Modulated SOA for Upstream: Similar to the aforementioned scheme, an optical carrier is combined with an RF signal, generated by means of PM, and sent downstream where an FBG is used at the RAU to reflect the optical carrier and pass the RF signal. The reflected optical carrier is amplified and directly modulated with upstream data using a semiconductor optical amplifier (SOA).

The use of a colorless (i.e., wavelength-independent) SOA as an amplifier and modulator for upstream transmission provides a promising low-cost RoF solution that is easy to maintain [16].

R&F Technologies. R&F-based FiWi access networks may deploy a number of enabling optical and wireless technologies.

Optical Technologies. Apart from PONs, the following optical technologies are expected to play an increasingly important role in the design of a flexible and cost-effective optical backhaul for FiWi networks [17].

– Tunable Lasers: Directly modulated external cavity lasers, multisection distributed feedback (DFB)/distributed Bragg reflector (DBR) lasers, and tunable VCSELs can be used as tunable lasers which render the network flexible and reconfigurable and help minimize production cost and reduce backup stock.
– Tunable Receivers: A tunable receiver can be realized by using a tunable optical filter and a broadband photodiode. Other more involved implementations exist (see [17]).
– Colorless ONUs: Reflective SOAs (RSOAs) can be used to build colorless ONUs that remotely modulate optical signals generated by centralized light sources.
– Burst-Mode Laser Drivers: Burst-mode transmitters are required for ONUs. They have to be equipped with laser drivers that provide fast burst on/off speed, sufficient power suppression during idle period, and stable, accurate power emission during burst transmission.
– Burst-Mode Receivers: Burst-mode receivers are required at the central optical line terminal (OLT) of a PON and must exhibit a high sensitivity, wide dynamic range, and fast time response to arriving bursts. Among others, design challenges for burst-mode receivers include dynamic sensitivity recovery, fast level recovery, and fast clock recovery.

Wireless Technologies. A plethora a broadband wireless access technologies exist [18]. Currently, the two most important ones for the implementation of the wireless part of FiWi networks are WiFi and WiMAX.

– WiFi: Due to the use of unlicensed frequency bands (2.4 GHz with 14 distinct channels) in IEEE 802.11b/g, providing up to 11/54 Mbps data rate, wireless LANs, also referred to as WiFi networks, have gained much attention. The initial IEEE 802.11 PHY layer includes: (*i*) Frequency Hopping Spread Spectrum (FHSS), (*ii*) Direct Sequence Spread Spectrum (DSSS), and (*iii*) Infrared (IR). IEEE 802.11b uses High-Rate DSSS (HR-DSSS), while IEEE 802.11g deploys Orthogonal Frequency Division Multiplexing (OFDM). The IEEE 802.11 MAC layer deploys the above mentioned DCF as a default access technique. In this contention based scheme, subscriber stations (STAs) associated with the Access Point (AP) use their air interfaces for sensing channel availability. If the channel is idle, the source STA sends its data to the destination STA through the associated AP. If more than one STA try to access the channel simultaneously a collision occurs. The standard uses the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) mechanism to avoid collisions. Point Coordination Function (PCF) is another technique that may be used in the MAC layer. In PCF, the data transmission is arbitrated in two modes: (*i*) centralized mode, where the AP polls each STA in a round-robin fashion, and (*ii*) contention-based mode, which works similarly to DCF. In addition, the Request To Send (RTS)/Clear To Send (CTS) mechanism is applied to solve the hidden node problem.

– WiMAX: The initial IEEE 802.16 WiMAX standard was established in the frequency band of 10-66 GHz, providing up to 75 Mbps data rate line-of-sight (LOS) connections in both point-to-multipoint (PMP) and mesh modes. IEEE 802.16a provides non-LOS connections in the frequency band of 2-11 GHz (licensed and unlicensed). The WiMAX PHY layer uses WirelessMAN-OFDMA (Orthogonal Frequency Division Multiple Access) and transfers bidirectional data by means of Time Division Duplex (TDD) or Frequency Division Duplex (FDD). IEEE 802.16 is a connection-oriented standard, i.e., prior to transmitting data between Subscriber Stations (SSs) and Base Station (BS), connections must be established. Each connection is identified by a 16-bit Connection Identifier (CID). The MAC layer is responsible for assigning CIDs as well as allocating bandwidth between SSs. It consists of the following three sublayers: (*i*) Convergence Sub-layer (CS), whereby different higher-layer protocols are implemented in different CSs, e.g., ATM CS and packet CS are used for ATM and Ethernet networks, respectively; (*ii*) Common Part Sub-layer (CPS), which is responsible for bandwidth allocation and generating MAC Protocol Data Units (PDUs); and (*iii*) security sub-layer. In the PMP mode, the requested services of each SS are first registered during the initialization phase and subsequently the connections are established. If a given SS changes its services, additional connections can be established in the network. Each connection is associated with a Service Flow (SF). An SF is defined based on available scheduling services and includes a set of QoS parameters, an SF Identifier (SFID), and a CID. To implement wireless mesh networks (WMNs), two scheduling types are used: (*i*) centralized and (*ii*) distributed. In the centralized scheduling mode, such as the PMP, each Mesh-SS (MSS) sends its request to the Mesh-BS (MBS) that manages the network. In the distributed scheduling mode, each MSS distributes its scheduling information and one-hop neighbors among all its adjacent MSSs. A three-way handshake mechanism is deployed for bandwidth allocation. Coordinated (collision-free) and uncoordinated (non-collision-free) methods are used for distributed scheduling. The two different mesh scheduling methods can be applied together by subdividing the data part of the frame into two parts, one for centralized scheduling and another one for distributed scheduling.

3.2 State of the Art

Cellular networks used for fast moving users, e.g., train passengers, suffer from frequent hand-overs when hopping from one base station to another one. The frequent hand-overs cause numerous packet losses, resulting in a significantly decreased network throughput. An interesting approach to solve this problem for train passengers is the use of an RoF network installed along the rail tracks in combination with the so-called moving cell concept [19]. The proposed solution provides high-capacity wireless services to high-speed train passengers using a hierarchical approach that consists of a wireless link between the railway and the train on the one hand and a separate wireless link between the train and the users on the other hand. In each train carriage, one or more WLAN access points are used to provide Internet connection.

Fig. 3 depicts the moving cell based RoF network architecture for train passengers. Several RAUs are located along the rail tracks. An optical wavelength division multiplexing (WDM) ring interconnects the RAUs with the central station where all processing is performed. Each RAU deploys an optical add-drop multiplexer (OADM) fixed tuned to a separate wavelength channel. That is, each RAU is allocated a separate dedicated wavelength channel for transmission and reception to and from the central station. At the central station, a WDM laser generates the desired wavelengths in order to reach the corresponding RAUs. The generated wavelengths are optically switched and passed to an array of RF modulators, one for each RAU. The modulated wavelengths are multiplexed onto the optical fiber ring and received by each addressed RAU on its assigned wavelength. An RAU retrieves the RF signal and transmits it to the antennas of a passing train. In the upstream direction, the RAUs receive all RF signals and sends them to the central station for processing. By processing the received RF signals, the central station is able to keep track of the train location and identifying the RAU closest to the moving train.

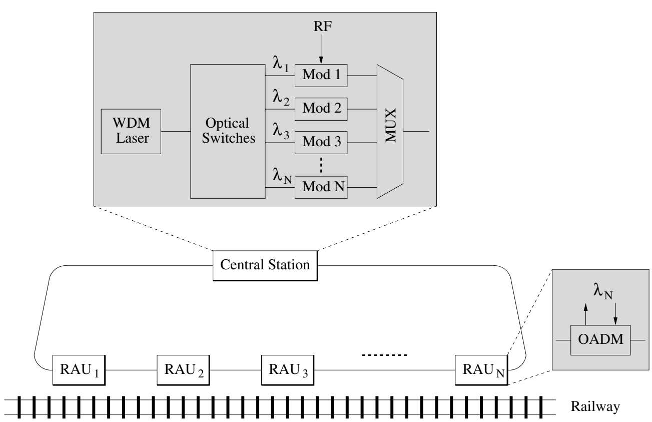

Fig. 3. Moving cell-based RoF network architecture for train passengers [19]

In conventional cellular radio networks, a hand-over would take place whenever the train crosses the cell boundary between two neighboring RAUs. To avoid hand-overs, the applied concept of moving cells lets a cell pattern move together with the passing train such that the train can communicate on the same RF frequencies during the whole connection without requiring hand-overs. The central station implements the moving cells by subsequently sending the RF frequencies used by the train to the next RAU following in the direction the train is moving. Based on the received upstream RF signals, the central station is able to track the location of the train and assign downstream RF signals to the corresponding RAU closest to the train such that the train and moving cells move along in a synchronous fashion.

Fig. 4 shows a two-level bidirectional path-protected ring R&F architecture for dense WDM/subcarrier multiplexing (SCM) broadband FiWi networks [20]. In this architecture, the CO interconnects remote nodes (RN) via a dual-fiber ring. Each RN cascades wireless access points (WAPs) through concentration nodes (CNs), where each WAP offers services to mobile client nodes (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

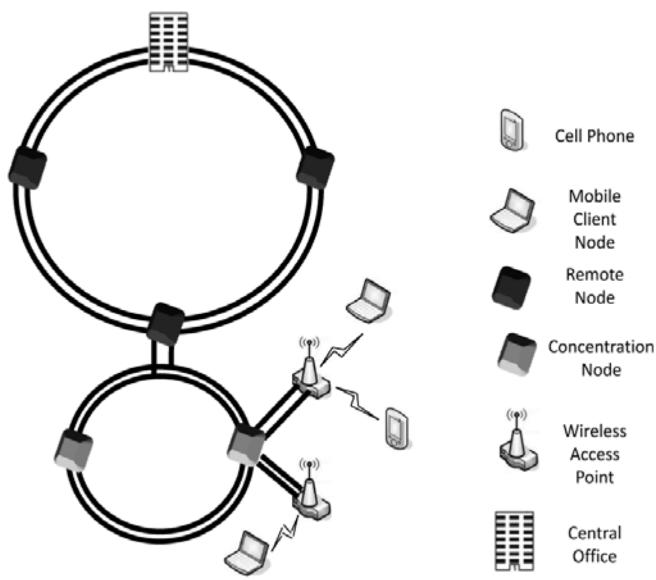

Fig. 4. Optical interconnected bidirectional fiber rings integrated with WiFi-based wireless access points [20]

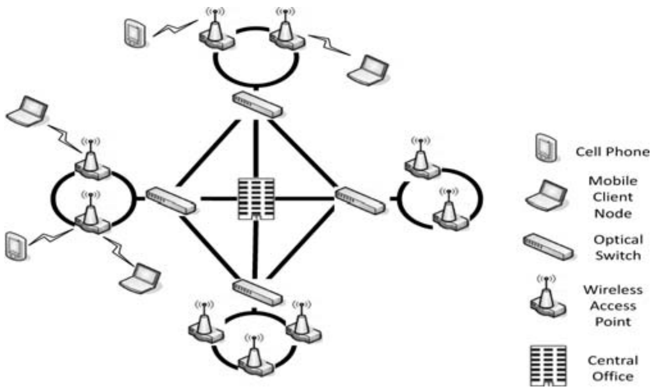

Fig. 5. Optical hybrid star-ring network integrated with WiFi-based wireless access points [21]

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.

Fig. 5 depicts an R&F-based hybrid FiWi network topology that combines optical star and ring networks [21]. 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 point-to-point 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 [22] consists of an optical WDM backhaul ring with multiple single-channel or multichannel PONs attached to it, as shown in Fig. 6. An OADM is used to connect the OLT of each PON to the WDM ring. Wireless gateways are used to realize an R&F network that bridges the PONs to a WiFi-based WMN. In the downstream direction, data packets are routed from the CO to the wireless gateways through the optical backhaul and are 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

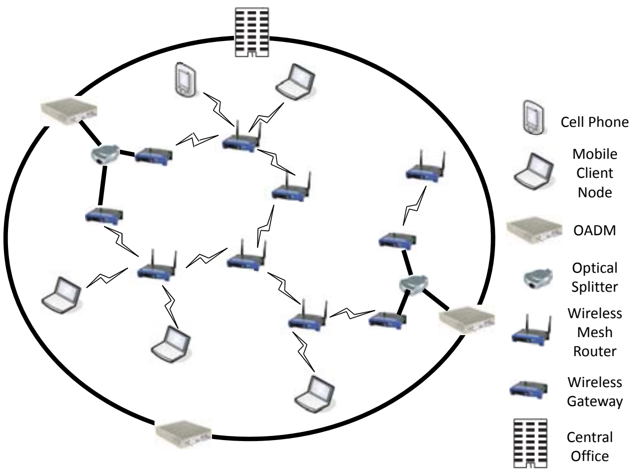

Fig. 6. Optical unidirectional WDM ring interconnecting multiple PONs integrated with a WiFi-based wireless mesh network [22]

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 time division multiplexing (TDM) PONs may be upgraded to WDM PONs. If some PONs are heavily loaded and others have less traffic, some heavy-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 hand-overs.

4 SuperMAN

As we have seen in the previous section, most previously reported FiWi networks used WiFi technologies for the wireless part. Only a few reported FiWi networks considered the deployment of WiMAX technologies. One notable example is the integration of single-channel TDM EPON and WiMAX networks. Several TDM EPON-WiMAX integration approaches were outlined and discussed in [23], ranging from independent to unified connection-oriented architectures. The integration of TDM EPON and WiMAX access networks seems to be interesting due to the similarity of the two technologies. Both EPON and WiMAX networks typically have a point-to-multipoint topology with a central control station (OLT in EPON, BS in WiMAX) performing dynamic bandwidth allocation by means of centralized polling and scheduling. These similarities give rise to interesting convergence problems whose optimization is expected to lead to an improved FiWi network performance.

In our proposed FiWi network, we take a different approach. Given the similarities of EPON and WiMAX, we argue that the two technologies are more likely to target the same network segment rather than being cascaded to cover different network segments. In other words, we expect that network operators will make a choice between EPON and WiMAX depending on a number of factors, e.g., right-of-way. Furthermore, recall from Section 1 that EPON networks will bring fiber close or all the way to end users. It seems somewhat impractical to deploy a metropolitan-reach wireless technology such as WiMAX for realizing wireless drop lines of rather short length to or inside offices and homes. Instead, using next-generation low-cost WiFi technologies in conjunction with WDM-enhanced EPON access networks while integrating WiMAX with optical metropolitan area network (MAN) technologies appears to be a more promising approach, giving rise to a novel FiWi network architecture which we call SuperMAN.

Fig. 7 depicts the network architecture of SuperMAN. It builds on our all-optically integrated Ethernet-based access-metro network, described at length in [24], extended by optical-wireless interfaces with next-generation WiFi and WiMAX networks. More specifically, the optical part of SuperMAN consists of an IEEE 802.17 Resilient Packet Ring (RPR) metro network that interconnects multiple WDM EPON access networks attached to a subset of RPR nodes. RPR is an optical dual-fiber bidirectional ring network that aims at combining Ethernet's statistical multiplexing gain, low equipment cost, and simplicity with SONET/SDH's carrier-class functionalities of high availability, reliability, and

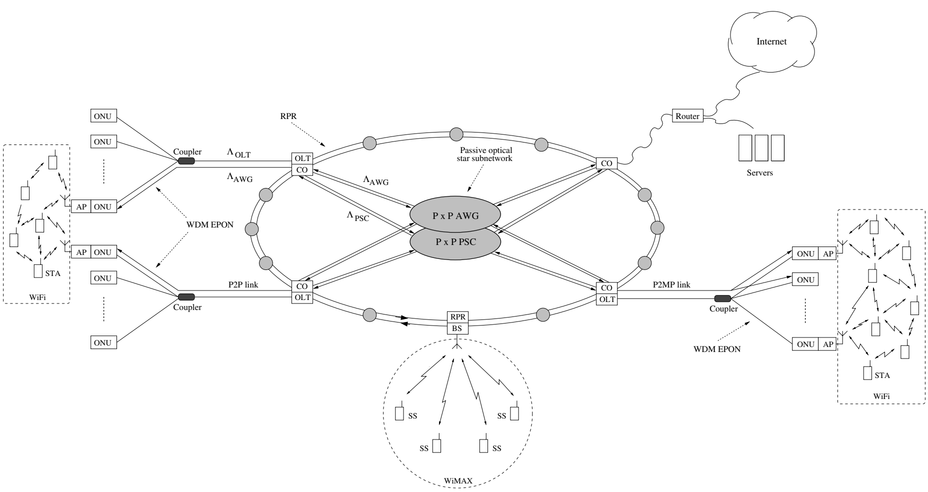

Fig. 7. SuperMAN architecture integrating next-generation WiFi technologies with WDM EPON and next-generation WiMAX technologies with RPR

profitable TDM (voice) support. In RPR, destination stripping is deployed to improve spatial reuse of bandwidth and thus increase the capacity of the network. Each of the attached WDM EPONs has a tree topology with the OLT at the root tree being collocated with one of the P COs. No particular WDM architecture is imposed on the ONUs, thus allowing the decision to be dictated by economics, state-of-the-art transceiver manufacturing technology, traffic demands, and service provider preferences. The recommended WDM extensions to the IEEE 802.3ah MultiPoint Control Protocol (MPCP), described in greater detail in [25], guarantee backward compatibility with legacy TDM EPONs and enable the OLT to schedule transmissions to and receptions from ONUs on any supported wavelength channel. The optical access-metro network lets low-cost PON technologies follow low-cost Ethernet technologies from access networks into metro networks by interconnecting the P collocated OLTs/COs with a passive optical star subnetwork whose hub consists of an athermal wavelength-routing $P \times P$ arrayed waveguide grating (AWG) in parallel with a wavelength-broadcasting $P \times P$ passive star coupler (PSC). It is important to note that in each WDM EPON two different sets of wavelengths, Λ_{OLT} and Λ_{AWG}, are used. The first wavelength set, Λ_{OLT}, is used for upstream and downstream transmissions between ONUs and respective OLT residing in the same WDM EPON. Whereas the second set, Λ_{AWG}, comprises wavelengths that optically bypass the collocated OLT/CO and allow ONUs residing in different WDM EPONs to communicate all-optically with each other in a single hop across the AWG of the star subnetwork, provided the ONUs are equipped with transceivers operating on these wavelengths. We finally note that similar to IEEE 802.3ah EPON, the optical part of SuperMAN is not restricted to any specific dynamic bandwidth allocation (DBA) algorithm. A plethora of DBA algorithms for WDM EPONs exist [26]. These DBA algorithms need to be adapted to SuperMAN. The aforementioned optical part of SuperMAN interfaces with next-generation WiFi and WiMAX networks. Both optical-wireless interfaces are described in greater detail in the following.

4.1 RPR/WiMAX Interface

As shown in Fig. 7, some of the RPR nodes may interface with WiMAX rather than EPON access networks. Fig. 8 depicts the optical-wireless interface between RPR and WiMAX networks in greater detail, where an integrated rate controller (IRC) is used to connect an RPR node to a WiMAX BS.

In RPR, packets undergo optical-electrical-optical (OEO) conversion at each ring node. An RPR node deploys in general two separate electrical transit queues, one primary transit queue (PTQ) and one secondary transit queue (STQ), for service differentiation. In addition, an electrical stage queue is used to store traffic ready to be sent by the RPR station. The RPR scheduler gives priority to in-transit ring traffic over station traffic such that in-transit packets are not lost due to buffer overflow. Furthermore, RPR deploys a distributed fairness control protocol that dynamically throttles traffic in order to achieve network-wide fairness while maintaining spatial reuse.

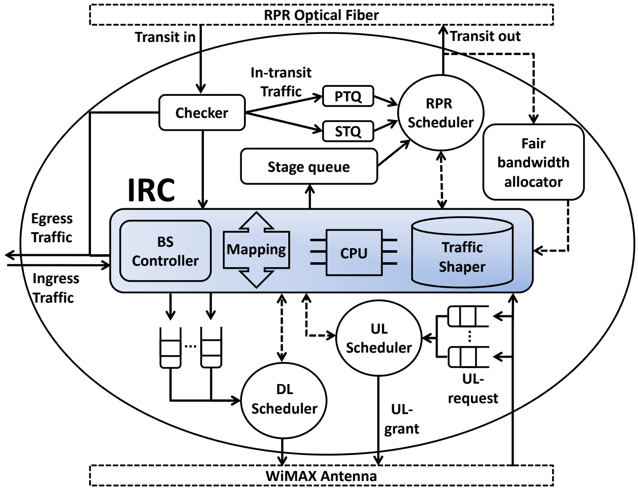

Fig. 8. Optical-wireless interface between RPR and WiMAX networks

The WiMAX BS deploys a downlink (DL) scheduler and an uplink (UL) scheduler, whereby the latter one processes UL requests from and sends UL grants to its attached SSs. In our ongoing work, we consider IEEE 802.16e and the emerging amendment IEEE 802.16m. The first one adds mobility support to conventional IEEE 802.16d WiMAX networks, while the latter one provides increases the data rate to 1 Gb/s.

The IRC in Fig. 8 plays a key role in our ongoing work on integrating RPR and WiMAX technologies. The IRC comprises a BS controller, traffic class mapping unit, CPU, and traffic shaper. It will be used to seamlessly integrate both technologies and jointly optimize the RPR scheduler and WiMAX DL and UL schedulers.

4.2 WDM EPON/Next-Generation WiFi Interface

Recall from Section 2 that WiFi-based RoF networks can sustain acceptable throughput performance only if the inserted fiber does not exceed a certain maximum length. Due to the fact that EPONs can have a reach of up to 20 km, the WDM EPON tree networks with WiFi extensions are realized as R&F networks, where each WiFi-based network operates independently of its attached WDM EPON tree network. In our ongoing work, we focus on the MAC enhancements of next-generation IEEE 802.11n WLANs and path selection algorithms for IEEE 802.11s WLAN mesh networks.

Next-generation WLANs will offer a throughput of at least 100 Mb/s measured at the MAC service access point (SAP). The IEEE standard 802.11n isn't expected to be approved until March 2009, but devices built to the current 802.11n draft will require only software upgrades to be compliant with the ratified standard. The draft provides both PHY and MAC enhancements. By using MIMO-OFDM and channel bonding, 802.11n WLANs offer raw data rates of about 600 Mb/s at the physical layer. To achieve a net MAC throughput of 100 Mb/s and higher, 802.11n WLANs allow wireless stations for the truncation of transmission opportunities (TXOPs), reverse direction (i.e., bidirectional TXOP), and use of a reduced interframe space (RIFS) to decrease the dead time between frames (a TXOP, specified in IEEE 802.11e, is a time interval during which a wireless station following a single channel access is allowed to send multiple data frames). The most important MAC enhancement of next-generation WLANs is frame aggregation. In 802.11n, the following two methods exist for frame aggregation: (*i*) aggregate MAC protocol data unit (A-MPDU), and (*ii*) aggregate MAC service data unit (A-MSDU). A-MPDU concatenates up to 64 MPDU subframes into a single physical layer SDU, provided all constituent MPDUs are destined to the same receiver. A-MSDU concatenates multiple MSDU subframes into a single MPDU, whereby all constituent MSDUs not only have to be destined to the same receiver but also must have the same traffic identifier (TID), i.e., the same QoS level. A-MPDU and A-MSDU can be used separately or jointly to increase the MAC throughput of next-generation WLANs.

As shown in Fig. 7, SuperMAN deploys a next-generation 802.11n WLAN mesh network. The emerging amendment IEEE 802.11s aims at specifying a wireless distribution system (WDS) among WLAN APs which can be used to realize municipal networks that provide public wireless access throughout cities, neighborhoods, and campuses. IEEE 802.11s introduces a new mesh frame format and radio-aware routing framework which uses the so-called Hybrid Wireless Mesh Protocol (HWMP) as default routing protocol. HWMP works on layer 2, uses MAC addresses for path selection, and contains both reactive and proactive routing components. In SuperMAN, proactive routing can be used to configure routing trees toward the collocated AP/ONU(s) that act as mesh portals bridging the WLAN mesh network to the optical (wired) WDM EPON access network. For intra-mesh communication between wireless stations, a given mesh portal (i.e., AP/ONU) may apply reactive routing by setting up a direct route between the involved wireless stations, thereby eliminating the need to send intra-mesh traffic through the mesh portal. It is important to note that the routing framework of IEEE 802.11s is extensible. Thus, other routing protocols and routing metrics can be deployed in order to optimize network performance according to given traffic demands and usage scenarios.

In our ongoing work, we study integrated hybrid path selection algorithms for SuperMAN that take both proactive and reactive components as well as different routing metric combinations into account. Particular attention will be paid to the design and performance evaluation of QoS-aware scheduling algorithms that ensure QoS continuity across the WDM EPON/next-generation WiFi interface and provide end-to-end QoS assurances across SuperMAN.

5 Conclusions

Hybrid optical-wireless FiWi networks form a powerful future-proof platform that provides a number of advantages. Introducing optical fiber into broadband wireless access networks helps relieve emerging bandwidth bottlenecks in today's wireless backhaul due to increasing traffic loads generated by new applications, e.g., iPhone. 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 independently of each other, thus potentially leading to major cost savings.

More interestingly, and certainly somewhat controversially, by paving all the way to and penetrating into homes and offices with high-capacity fiber and connecting wireless laptops and handhelds with high-throughput WiFi technologies to high-speed optical wired networks, SuperMAN, and FiWi networks in general, give access to the ever increasing processing and storage capabilities of memory and CPUs of widely used desktops, laptops, and other wireless handhelds, e.g., Wii. Note that nowadays desktop and laptop computers commonly operate at a clock rate of 1 GHz with a 32-bit wide backplane, resulting in an internal flow of 2-8 Gb/s with today's limited hard drive I/O, while future desktops and laptops are expected to reach 100 Gb/s by 2010 [7]. At present, these storage and processing capabilities are quite often utilized only in part. After bridging the notorious first/last mile bandwidth bottleneck, research focus might shift from bandwidth provisioning to the exploitation of distributed storage and processing capabilities available in widely used desktops and laptops, especially as we are about to enter the Petabyte age with sensors everywhere collecting massive amounts of data [27]. As an early example for this shift can be viewed the design of P2P on-line game architectures that have begun to increasingly receive attention, where players' computing resources are utilized to improve the latency and scalability of networked on-line games, whose groundbreaking technologies might also be used to realize the future 3D Internet. On the other hand, in-house computer facilities might be replaced with computer utilities as in-house generators were replaced with electrical utilities [28]. Indeed, utility-supplied computing, e.g., Google, will continue to have an increasing impact on society and replace personal computer facilities unless new services and applications are developed that capitalize on them. Toward this end, it is important that FiWi networks are built using low-cost, simple, open, and ubiquitous technologies which allow all end users to have broadband access and to create unforeseen services and applications that help stimulate innovation, generate revenue, and improve the quality of our every-day lives, while at the same time minimizing the associated technical, economical, societal, and personal risks.

References

1. Koonen, T.: Fiber to the Home/Fiber to the Premises: What, Where, and When. Proceedings of the IEEE 94(5), 911–934 (2006)
2. Cioffi, J.M., Jagannathan, S., Mohseni, M., Ginis, G.: CuPON: The Copper Alternative to PON 100 Gb/S DSL Networks. IEEE Communications Magazine 45(6), 132–139 (2007)
3. Green, P.E.: Optical Networking Update. IEEE Journal on Selected Areas in Communications 14(5), 764–779 (1996)

4. Shinohara, H.: Broadband Access in Japan: Rapidly Growing FTTH Market. IEEE Communications Magazine 43(9), 72–78 (2005)
5. Koike, Y., Ishigure, T.: High-Bandwidth Plastic Optical Fiber for Fiber to the Display. IEEE/OSA Journal of Lightwave Technology 24(12), 4541–4553 (2006)
6. Ramaswami, R.: Optical Networking Technologies: What Worked and What Didn't. IEEE Communications Magazine 44(9), 132–239 (2006)
7. Green, P.E.: Fiber To The Home—The New Empowerment. John Wiley & Sons, Inc., Chichester (2006)
8. Chu, T.-S., Gans, M.J.: Fiber Optic Microcellular Radio. IEEE Transactions on Vehicular Technology 40(3), 599–606 (1991)
9. Wu, J., Wu, J.-S., Tsao, H.-W.: A Fiber Distribution System for Microcellular Radio. IEEE Photonics Technology Letters 6(9), 1150–1152 (1994)
10. Tang, P.K., Ong, L.C., Alphones, A., Luo, B., Fujise, M.: PER and EVM Measurements of a Radio-Over-Fiber Network for Cellular and WLAN System Applications. IEEE/OSA Journal of Lightwave Technology 22(11), 2370–2376 (2004)
11. Lethien, C., Loyez, C., Vilcot, J.-P.: Potentials of Radio over Multimode Fiber Systems for the In-Buildings Coverage of Mobile and Wireless LAN Applications. IEEE Photonics Technology Letters 17(12), 2793–2795 (2005)
12. Lin, C.-T., Chen, J., Peng, P.-C., Peng, C.-F., Peng, W.-R., Chiou, B.-S., Chi, S.: Hybrid Optical Access Network Integrating Fiber-to-the-Home and Radio-Over-Fiber Systems. IEEE Photonics Technology Letters 19(8), 610–612 (2007)
13. Dang, B.L., Niemegeers, I.: Analysis of IEEE 802.11 in Radio over Fiber Home Networks. In: Proc. IEEE Conference on Local Computer Networks, pp. 744–747. IEEE Press, Sydney (2005)
14. Kalantarisabet, B., Mitchell, J.E.: MAC Constraints on the Distribution of 802.11 using Optical Fibre. In: Proc. European Conference on Wireless Technology, pp. 238–240. IEEE Press, Los Alamitos (2006)
15. Henry, P.S.: Integrated Optical/Wireless Alternatives for the Metropolitan Environment. IEEE Communications Society Webinar (2007)
16. Jia, Z., Yu, J., Ellinas, G., Chang, G.-K.: Key Enabling Technologies for Optical-Wireless Networks: Optical Millimeter-Wave Generation, Wavelength Reuse, and Architecture. IEEE/OSA Journal of Lightwave Technology 25(11), 3452–3471 (2007)
17. Kazovsky, L.G., Shaw, W.-T., Gutierrez, D., Cheng, N., Wong, S.-W.: Next-Generation Optical Access Networks. IEEE/OSA Journal of Lightwave Technology 25(11), 3428–3442 (2007)
18. Kuran, M.S., Tugcu, T.: A Survey on Emerging Broadband Wireless Access Technologies. Computer Networks 51(11), 3013–3046 (2007)
19. Lannoo, B., Colle, D., Pickavet, M., Demeester, P.: Radio-over-Fiber-Based Solution to Provide Broadband Internet Access to Train Passengers. IEEE Communications Magazine 45(2), 56–62 (2007)
20. Lin, W.-P., Kao, M.-S., Chi, S.: A Reliable Architecture for Broad-Band Fiber-Wireless Access Networks. IEEE Photonics Technology Letters 15(2), 344–346 (2003)
21. Bhandari, S., Park, E.K.: Hybrid Optical Wireless Networks. In: Proc. International Conference on Networking, International Conference on Systems, and International Conference on Mobile Communications and Learning Technologies, pp. 113–117. IEEE Press, Mauritius (2006)

22. Shaw, W.-T., Wong, S.-W., Cheng, N., Balasubramanian, K., Zhu, X., Maier, M., Kazovsky, L.G.: Hybrid Architecture and Integrated Routing in a Scalable Optical-Wireless Access Network. IEEE/OSA Journal of Lightwave Technology 25(11), 3443–3451 (2007)
23. Shen, G., Tucker, R.S., Chae, C.-J.: Fixed Mobile Convergence Architectures for Broadband Access: Integration of EPON and WiMAX. IEEE Communications Magazine 45(8), 44–50 (2007)
24. Maier, M., Herzog, M., Reisslein, M.: STARGATE: The Next Evolutionary Step Toward Unleashing the Potential of WDM EPONs. IEEE Communications Magazine 45(5), 50–56 (2007)
25. McGarry, M.P., Maier, M., Reisslein, M.: WDM Ethernet Passive Optical Networks. IEEE Communications Magazine 44(2), S18–S25 (2006)
26. McGarry, M.P., Reisslein, M., Maier, M.: Ethernet Passive Optical Network Architectures and Dynamic Bandwidth Allocation Algorithms. IEEE Communications Surveys and Tutorials (to appear)
27. The Petabyte Age. WIRED, p. 106 (July 2008)
28. Carr, N.: The Big Switch: Rewiring the World, from Edison to Google. W. W. Norton & Company, Inc. (2008)