INVITED PAPER

Fiber to the Home/Fiber to the Premises: What, Where, and When?

The solution may be direct fiber to each home, or shared multiplexed fiber links, or hybrid fiber-copper, -coax, or, perhaps, radio-over-fiber.

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ABSTRACT | After conquering the core and metropolitan networks, fiber is now penetrating into the access domain. Its low loss and huge bandwidth enable the delivery of any current and foreseeable set of broadband services, and also make it a nice match to the wireless link to the end user. Cost effectiveness is a key issue, and will be decisive for the network topology choices. Point-to-point may be the most cost-effective for short-reach access, whereas point-to-multipoint may be the most interesting at medium- to long-reach access, or when line terminations in the local exchange become a key issue. A number of optical techniques being deployed for shared-fiber multiple access are discussed, based on time slot multiplexing, frequency slot multiplexing, code division multiplexing, and wavelength multiplexing, including their application in fiber to the home/fiber to the premises (FTTH/FTTP) networks for fast data transfer (asynchronous transfer mode (ATM) or Ethernet based) and for broadband service distribution (such as CATV). In the research laboratories, techniques aiming at next-generation optical access are being studied, such as wavelength routing for flexible capacity allocation and easily adaptable hosting of services and service providers, and radio-over-fiber techniques creating a powerful symbiosis of the fiber world and the wireless world by enabling centralized radio signal processing.

KEYWORDS | Broadband access; fiber to the home; multiple access; passive optical networks; radio over fiber; wavelength multiplexing

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I. INTRODUCTION

The set of communication services being offered to residential homes has seen rapid expansion in the last decades. Customers are no longer only interested in voice telephony, broadcast television, and radio; they are also increasingly asking for always-on fast Internet communication, video-based multimedia, fast peer-to-peer file transfer, high definition multimedia on-line gaming, etc. The growth of the population of elderly people is asking for more medical care, and to prevent overload of hospitals and health clinics, there is a trend to keep elderly people longer in their home environment. For this, remote observation by means of video surveillance and other telemonitoring means generate additional communication needs. Other social trends such as teleworking in order to reduce rush hour traffic are requiring higher capacity to residential homes as well. The tailoring of services to individual needs, and the emergence of several competing operators due to liberalization, are contributing to the growth of access network traffic as well.

The conventional access network infrastructures, namely the twisted-pair telephony networks and the coaxial cable CATV networks, are having a hard time to keep up with these traffic demands. Digital subscriber line techniques (ADSL, VDSL, etc.) and cable modem techniques are evolving into higher speeds, but at the cost of a shorter reach. The unique properties of optical single-mode fiber, being its low loss and extremely wide inherent bandwidth, make it the ideal candidate to meet the capacity challenges for now and the foreseeable future. Single-mode fiber has already been adopted as the workhorse in core and metropolitan networks, and is increasingly penetrating the access domain as well. Economical considerations are key when decisions on fiber introduction have to be made (see e.g., [1]). The costs of digging and ducting are the major cost items in access networks, outweighing by far the costs of the transmission medium and the line terminating equipment. Civil works typically may take some 85% of fiber to the home (FTTH) first installed network costs, while the fiber cable and the optical components take only 3%; the remainder is taken by other hardware, installation activities, and other services. Hence, in green-field situations, the costs of introducing FTTH may not differ much from, e.g., twisted copper pair or coaxial cable access solutions. Moreover, the costs of fiber-optic line-terminating transceivers are coming down rapidly. FTTH's operational costs may be lower, as it needs less active equipment in the field which needs maintenance.

A fiber link can basically handle any kind of access traffic, so installing fiber is an insurance for the future ("future-proof," or "forecast-tolerant," investment). Hence, in many green-field situations, single-mode fiber is being installed up to the home. For upgrading existing copper networks, however, the situation is less clear. To reap the maximum return on the investments made before in these networks, much effort is spent in introducing more advanced copper line techniques in the last link to the end user. Also, fixed wireless access solutions bridging wirelessly the gap to the end user are considered. However, the decreased reach of these solutions often necessitates a further penetration of fiber in the access feeder links, leading to hybrid fiber access networks with decreasing length of copper lines to the homes, or to fiber-fed wireless access. E.g., in fiber to the curb (FTTC) networks, the fiber may run up to a street cabinet, from where on an ADSL line on twisted copper pairs (or VDSL line in shorter links) goes to the home. Or in hybrid fiber coax (HFC) networks fiber is running up to CATV street cabinets, and from there coaxial cables run to the homes.

For short reach links, such as inside buildings, multimode fiber may offer the advantage of easier handling than single-mode fiber (in particular, in installation activities such as splicing), due to its larger core diameter (50 or 62.5 μm, versus some 9 μm) [2]. Its bandwidth-times-length product is smaller than that of single-mode fiber; however, this is not a significant issue in short-reach links. Further gains in ease of handling may be obtained by using multimode polymer optical fiber (POF), due to its ductility and its even langer core sizes (beyond 100 μm).

This paper gives first an overview of basic fiber-optic access network architectures, and discusses main basic multiple access mechanisms: using time slots, electrical frequency slots, wavelength slots, or code slots. Of these, time-slotted multiple access techniques will be treated in more depth, covering ATM-, Ethernet- and gigabit-based passive optical networks (ATM-PON, EPON, and GPON, respectively). Next, frequency-slotted access such as applied in hybrid fiber coax (HFC) networks will be addressed. Subsequently, next to the static wavelength-slotted WDM-PON, attention will be paid to access techniques that are mostly still under research for next-generation access networks: wavelength-slotted access with flexible wavelength routing for dynamic capacity allocation, and radio-over-fiber techniques for fiber-wireless networks. Finally, some speculative prospects for the more distant future will be given.

II. FIBER ACCESS NETWORK ARCHITECTURES

Basically, three architectures may be deployed for the fiber access network (see Fig. 1).

1) *Point-to-point* architecture, where individual fibers run from the local exchange to each home. Many fibers are needed, which entails high first installation costs, but also provides the ultimate capacity and the most flexibility to upgrade services for customers individually. In the local exchange, as many fiber terminals are needed as there are homes, so floor space and powering may become issues.
2) *Active star* architecture, where a single fiber carries all traffic to an active node close to the end users, from where individual fibers run to each cabinet/home/building. Only a single feeder fiber is needed, and a number of short branching fibers to the end users, which reduces costs; but the active node needs powering and maintenance. It also needs to withstand a wider range of temperatures than in-door equipment. In network upgrade scenarios, from the active node twisted copper pair lines (such as for ADSL up to some 4 km at speeds up to some 6 Mbit/s, or VDSL at speeds up to some 50 Mbit/s for lengths of some 500 m) may run, or coaxial cable lines (such as for HFC), or even wireless links to the customer [fixed wireless access (FWA)]. The active node may be located in a cabinet at the street curb site (fiber to the cabinet (FTTCab) or FTTC), or in the basement of, e.g., a multidwelling units building [fiber to the building (FTTB)] from where the communication traffic is run throughout the building by copper wired and wireless local area networks at 100+ Mbit/s speeds.
3) *Passive star* architecture, in which the active node of the active star topology is replaced by a passive optical power splitter/combiner that feeds the individual short branching fibers to the end users. In addition to the reduced installation costs of a single fiber feeder link, the completely passive nature of the outside plant avoids the costs of powering and maintaining active equipment in the field. This topology has therefore become a very popular one for introduction of optical fiber into access networks, and is widely known as the *passive optical network (PON)*.

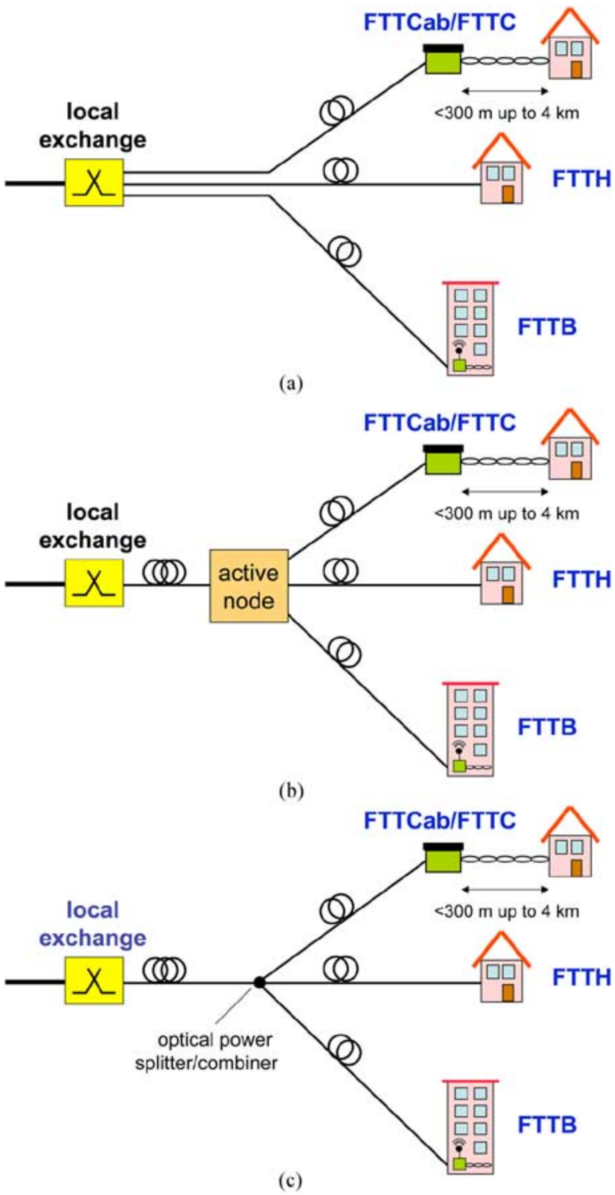

Fig. 1. ***Fiber access network architectures. (a) Point-to-point. (b) Active star. (c) Passive star (PON).***

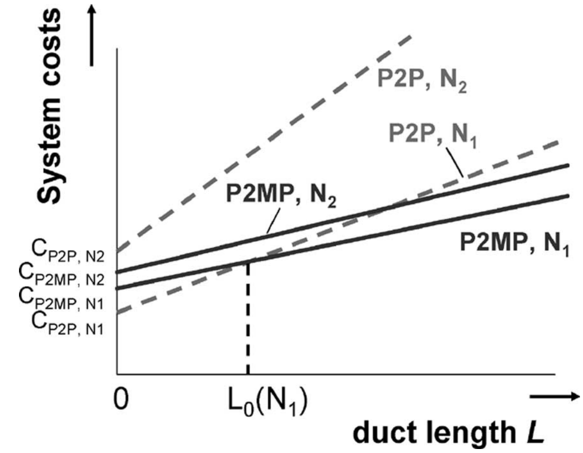

Fig. 2. ***General trend of installation costs versus the exchange-to-customer duct length, for P2P access network architectures and for P2MP architectures, and for connecting N customers ($N_2 > N_1$) ($C_{P2P,N2}$: costs of line terminating equipment in a P2P architecture connecting N_2 customers).***

Besides technical performance, economic considerations play a key role in deciding for a particular architecture. The duct pattern may be the same for all three architectures. However, in the point-to-point (P2P) architecture many fibers need to be installed throughout the network, whereas in the point-to-multipoint (P2MP) architectures (active and passive star ones) in the feeder part only one fiber is needed. The latter is advantageous as well when a complete feeder duct is destroyed by, e.g., a dragline machine: in the P2P architecture many fibers have to be identified and correctly reconnected, whereas in the P2MP architecture only a single fiber needs to be repaired. In the P2P architecture, for each home two optical line terminations are needed: one at the customer, and one in the exchange. In the P2MP architecture, in the exchange only a single termination is needed; however, the line terminations will be more expensive than the ones in the P2P architecture, as the sharing of the feeder fiber requires extra measures for avoiding traffic collisions. On the other hand, many customers share the costs of the line termination in the exchange. Qualitatively, the comparison of the installation costs of a P2P architecture versus those of a P2MP architecture may look as shown in Fig. 2. With increasing geographical area to be covered (so with increasing duct length), the system costs of a fiber-rich P2P architecture will grow faster than those of a P2MP architecture. Due to the higher complexity, the costs for a P2MP optical line terminal will, however, be higher than those of a P2P terminal. When the number of customers increases, the system costs of the P2P architecture grow faster than those of the P2MP architecture, as more fibers and more line terminating modules (and thus more floor space in the exchange) are needed. In the P2MP architecture, the costs rise slower as more fiber is needed only in the branches, and a bit more comprehensive (active or passive) splitter. Consequently, as shown in Fig. 2, there will be a certain duct length beyond which the installation costs of a P2MP architecture will be lower than those of a P2P architecture. This break-even duct length L_0 will be larger when more customers need to be fed. Hence, when a relatively small access area is to be fed, a P2P architecture may be cheaper to install, whereas for larger areas a P2MP architecture may be preferred.

In the P2P architecture and the P2MP active star architecture, each fiber link is carrying a data stream between two electro-optic converters only and the traffic streams of the users are multiplexed electrically at these

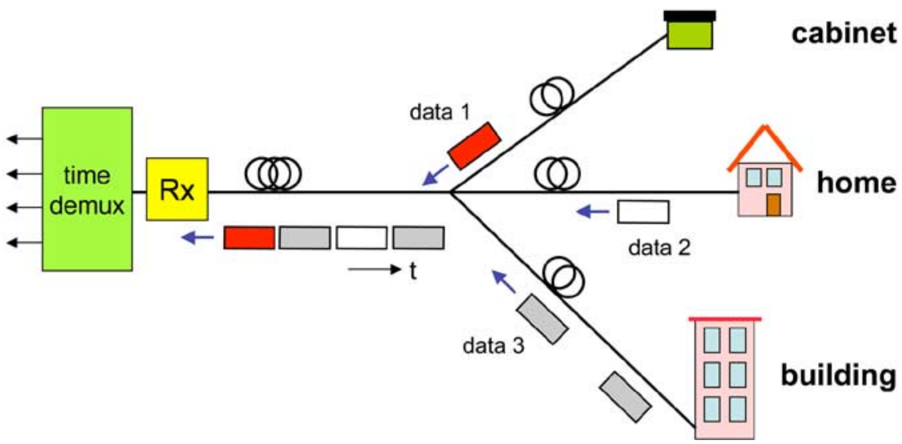

Fig. 3. *TDMA passive optical network.*

terminals. Therefore, there is no risk of collision of optical data streams. These point-to-point links are straightforward and can basically be realized with simple and cheap optical transceiver modules, which are readily available commercially.

In the P2MP passive star topology (the PON), however, the traffic multiplexing is done optically by merging the data streams at the passive optical power combiner. Collision of the individual data streams needs to be avoided by well-designed multiple access techniques. In the following section, several of these techniques for a PON will be discussed.

III. MULTIPLE ACCESS TECHNIQUES IN PONs

The common fiber feeder part of the PON is shared by all the optical network units (ONU-s) terminating the branching fibers. The traffic sent downstream from the optical line terminal (OLT) at the local exchange is simply broadcasted by means of the optical power splitter to every ONU. With longer fiber feeder lengths and thus higher feeder losses, the maximum possible split factor decreases.

Sending traffic from the ONU-s upstream to the local exchange requires accurate multiple access techniques in order to multiplex in a collision-free way the traffic streams generated by the ONU-s onto the common feeder fiber. Four major categories of multiple access techniques for fiber access networks have been developed:

- time division multiple access (TDMA);
- subcarrier multiple access (SCMA);
- wavelength division multiple access (WDMA);
- optical code division multiple access (OCDMA).

A. TDMA

In a *TDMA system*, as shown in Fig. 3, the upstream packets from the ONU-s are time-interleaved at the power splitting point, which requires careful synchronization of the packet transmission instants at the ONU-s. This synchronization is achieved by means of grants sent from the local exchange, which instruct the ONU when to send a packet. The correct timing of these submissions is achieved by ranging protocols, which sense the distance from each ONU to the local exchange. In the OLT at the local exchange, a burst mode receiver is needed which can synchronize quickly to packets coming from different ONU-s, and which also can handle the different amplitude levels of the packets due to differences in the path loss experienced. As the ONUs are sharing jointly the capacity of the OLT, the average capacity per ONU decreases when the number of ONUs grows.

B. SCMA

In an *SCMA system*, illustrated in Fig. 4, the various ONU-s modulate their packet streams on different electrical carrier frequencies, which subsequently modulate the light intensity of their laser diode. The packet streams are thus put into different frequency bands, which are demultiplexed again at the local exchange. Each frequency band constitutes an independent communication channel from an ONU to the OLT in the local exchange, and thus may carry a signal in a format different from that in an other channel (e.g., one channel may carry a high-speed digital data signal, and an other one an analog video signal). No time synchronization of the channels is needed. The laser diodes at the ONU-s may have nominally the same wavelength. When the wavelengths of the lasers are very close to each other, the frequency difference between them may result in beat noise products due to optical beating at the photodetector in the receiver. These noise products may interfere with the packet data spectrum. The wavelengths of the laser diodes have to be adjusted slightly different (e.g., by thermal tuning) in order to avoid this optical beat noise interference.

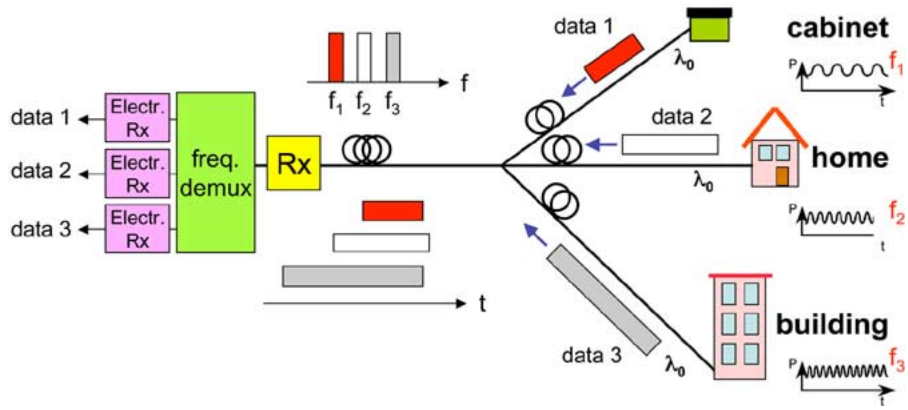

Fig. 4. *SCMA passive optical network.*

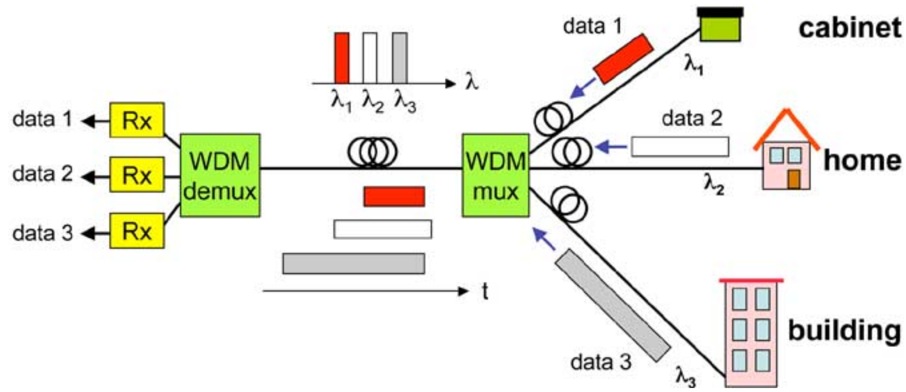

Fig. 5. *WDMA passive optical network.*

C. WDMA

In a *WDMA system* (see Fig. 5, also known as WDM PON), each ONU uses a different wavelength channel to send its packets to the OLT in the local exchange. The wavelength channels can be routed from the OLT to the appropriate ONU-s and backward by a wavelength demultiplexing/multiplexing device located at the PON splitting point. These wavelength channels constitute independent communication channels and thus may carry different signal formats; also no time synchronization between the channels is needed. The same wavelength channel may be used for upstream communication as well as for downstream simultaneously, provided that reflections in the link (which may occur at imperfect fiber splices and connectors) are negligible. The isolation requirements of the wavelength demultiplexer need to be sufficiently high to suppress crosstalk, e.g., between two different wavelength channels which are carrying high-speed digital data and analog video signals, respectively. The channel routing by the wavelength (de-)multiplexer at the network splitting point prohibits broadcasting of some channels to all ONU-s, as needed for instance for CATV signal distribution.

For upstream communication, every ONU needs a wavelength-specific laser diode, which increases costs, and complicates maintenance and stock inventory issues. Alternatively, universal colorless ONU concepts may be deployed which can benefit of economy of scale, and thus lower costs. Such a concept may use a light source with a broad spectrum at the ONU (e.g., a superluminescent LED), of which the in-field multiplexer cuts out the appropriate part of the spectrum. This "spectral slicing" approach [3] reduces the inventory problems, but also yields a reduced effective optical power available from the ONU and thus limits the reach of the system. Another colorless ONU concept is to use a reflective modulator at the ONU, which modulates the upstream data on a continuous light channel emitted at the appropriate wavelength by the OLT and returns it to the OLT [4]. Thus, no light source is needed at the ONU, which eases maintenance; but again the power budget is limited due to Rayleigh backscattering and other reflections from connectors and splices in the fiber link. This limit may be alleviated by using a reflective semiconductor optical amplifier (RSOA) of which the gain is modulated by the upstream data; the amplifier noise may then become the predominant limiting factor [5]. Alternatively, an injection-locked Fabry–Perót laser diode may be used [6].

D. OCDMA

In OCDMA, each ONU may use a specific optical code word to distinguish itself from the others. Two versions may be discerned: OCDMA using time-sliced code words, and OCDMA using spectrum-sliced code words.

In a *time-sliced OCDMA system*, each ONU uses a different signature sequence of short optical pulses, and this sequence is on–off modulated with the data to be transmitted. The duration of the sequence needs to be at least equal to that of a data bit, and thus a very high-speed signature sequence is needed to transmit moderate-speed data. This limits the reach of the system due to the increased impact of dispersion and the decreasing power budget at high line rates. In the OLT at the local exchange, the received signals are correlated with the known signature sequences, in order to demultiplex the data coming from the different ONU-s. As the signature codes may be not perfectly orthogonal, some crosstalk may occur.

In a *spectrum-sliced OCDMA system*, each ONU uses a different combination of spectral slices from a broadband optical source (such as an LED) of which the intensity is modulated with the data to be transmitted. In the OLT, an optical filter passing the same particular combination of spectral slices can be used to distinguish the data from that ONU. If the spectral slide codes are not perfectly orthogonal, some crosstalk will occur.

Two-dimensional coding by means of a combination of time and spectral slicing can increase the addressable number of ONUs [7].

E. Comparison of Multiple Access Techniques

TDMA systems have received the most attention for broadband access networks, as they are most suited for high-speed data transmission at relatively moderate complexity, and the required digital signal processing can be readily and cost-effectively accommodated in electronic integrated circuits. Two types of TDMA passive optical networks have been addressed extensively in standardization bodies: the ATM PON (APON) carrying native ATM cells in the G.983 standard series of ITU-T SG15, the Ethernet PON (EPON) carrying gigabit Ethernet packets in IEEE 802.3, and recently the gigabit PON (GPON) able to carry ATM as well as Ethernet packets with high line rates (up to 2.4 Gbit/s up- and downstream) and high efficiency in the G.984 standard series. These techniques will be discussed in more detail in Section IV.

Subcarrier multiplexing is particularly attractive for downstream broadband broadcasting, such as in hybrid fiber-coax (HFC) networks for distributing CATV services. In an interactive all-fiber point-to-multipoint access network, SCMA broadband communication in the upstream direction uses individual separate frequency bands, which puts high requirements on the frequency range and linearity of the user equipment. In addition, precautions have to be taken to avoid beat noise interference. Hence, SCMA is not commonly deployed in interactive all-fiber access networks. The application of subcarrier multiplexing techniques in hybrid fiber-coax CATV networks will be discussed in more detail in Section V.

WDMA offers the most powerful solution for multiple access, as it creates a virtual point-to-point topology on a physical point-to-multipoint topology. Thus, in analogy with point-to-point system concepts, this WDM-PON concept brings the advantages of easy scaling toward larger numbers of ONUs and of easy service upgrading per individual customer. It is also the most costly solution due to the additionally required wavelength-selective functions. However, the costs of WDM components are coming down, and the system concepts with colorless ONUs improve the economics of WDM-PON further. Using wavelength-based optical routing, flexible future-proof access networks can be implemented. Remarkable efficiency improvements of the system may be obtained when the wavelength routing can be adjusted remotely by the network operator, e.g., in order to reallocate capacity in response to fluctuating traffic demands, or to dynamically change service provisioning conditions in selected parts of the network (for service upgrades, leasing parts of the network, etc.). Dynamic WDMA thus is an attractive solution for next-generation access networks, and is being addressed in research. The static WDM-PON concept and the dynamic one will be discussed further in Section VI.

Time-sliced OCDMA puts high-speed requirements to the electro-optical terminals, due to the line rate being a multiple of the data rate. This leads to costly terminal equipment, and hence has not become popular for fiber-optic access networks. Spectrum-sliced OCDMA basically offers a similar functionality as spectrum-sliced WDMA, such as offering a parallel independent upstream path per ONU without timing synchronization issues. The OLT filter which implements the key of spectral slices in order to discern a particular ONU may offer a means for improved security. The broad spectrum, however, leads to increased dispersion and thus the line rate achievable is lower than that in a WDMA system.

IV. TDMA PON SYSTEMS

A. ATM PON

The full service access network (FSAN) group, a committee of currently 21 major telecommunication operators around the world, has been promoting the ATM PON (also termed APON or BPON) for broadband access networks since 1995.

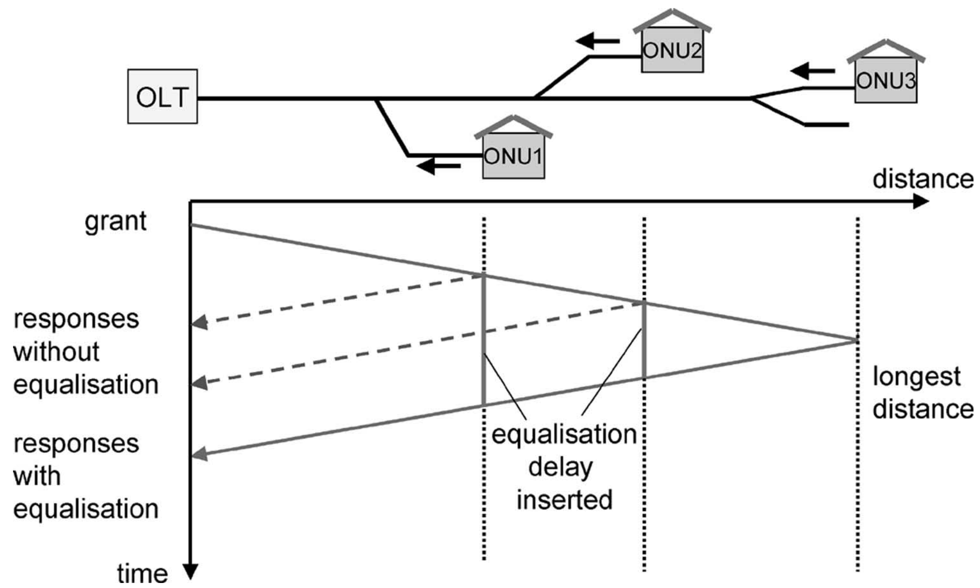

Fig. 6. ***Time ranging in a TDMA PON.***

1) ATM PON System Architecture: As laid down in the G.983.1 Recommendation of ITU-T [8], an ATM PON may have a downstream bitrate of 155 or 622 Mbit/s, and an upstream one of 155 Mbit/s. The maximum optical splitting ratio is 32 (may grow to 64), and the maximum fiber length between the OLT in the local exchange and an ONU is 20 km. The range in which this length is allowed to vary is from 0 to 20 km. Standard single mode fiber (G.652) is foreseen. Widely spaced wavelength multiplexing is used for separating the bidirectional traffic: the downstream traffic is positioned in the 1.5-μm wavelength band (allowing power boosting by men, and the upstream traffic in the 1.3-μm band. The 1.5-μm downstream band allows the use of erbium-doped fiber amplifiers for power boosting and hence improved link power budgets for broadcasting high-speed downstream services (e.g., video). The 1.3-μm upstream band allows the use of cheap uncooled Fabry–Perót laser diodes in the ONU-s.

In the downstream direction of a 155-Mbit/s down/155 Mbit/s up system, 54 ATM cells of 53 bytes each are fitted together with 2 physical layer operation, administration, and maintenance (PLOAM) cells of 53 bytes in a frame [8]. The PLOAM cells contain each 53 upstream grants. A grant permits an ONU to send an ATM cell. By sending these grants, the OLT controls at each ONU the transmission of the upstream packets, and can therefore assign dynamically a portion of the upstream bandwidth to each ONU. In a 622 Mbit/s down/155 Mbit/s up system, a frame contains four times as many cells (i.e., 216 ATM cells and 8 PLOAM cells). The downstream frame is broadcasted to all ONU-s. An ONU only extracts those cells that are addressed to it.

In the upstream frame, both for the 155-Mbit/s down/155-Mbit/s up system and for the 622-Mbit/s down/155-Mbit/s up system, 53 ATM cells are fitted of 53 bytes each plus an overhead of 3 bytes per cell. This overhead is used as guard time, as a delimiter and as preamble for supporting the burst mode receiver process in the local exchange.

The power budgets needed to bridge the fiber losses and the splitter losses are denoted by three classes of optical path losses: class A covering 5–20 dB of loss, class B 10–25 dB, and class C 15–30 dB. At the ONU, a launched optical power of −4 to +2 dBm is specified for class B, and −2 to +4 dBm for class C [9]. The ONU receiver sensitivity at 155 Mbit/s should be better than −30 dBm for class B, and −33 dBm for class C.

The ONU-s are usually positioned at different distances from the local exchange. Therefore, the upstream transmission of the packets from each ONU should be carefully timed, in such a way that the packets do not collide at the network splitter [8], [12]. The OLT has to measure the distance to each ONU for this, and then instructs the ONU to insert an equalizing transmission delay such that all distances from the ONU-s to the OLT are equal to the longest allowable distance (i.e., 20 km); see Fig. 6. To measure the distance to each ONU, the OLT emits a ranging grant to each ONU, and on receipt the ONU returns a ranging cell to the OLT. In this distance ranging process, the OLT can deduce the distance to each ONU from the round trip delay.

Each ONU sends an upstream cell upon the receipt of a grant. Because the path losses from each ONU to the OLT may be different, the power of the cells received by the OLT may vary considerably from cell to cell. The burst

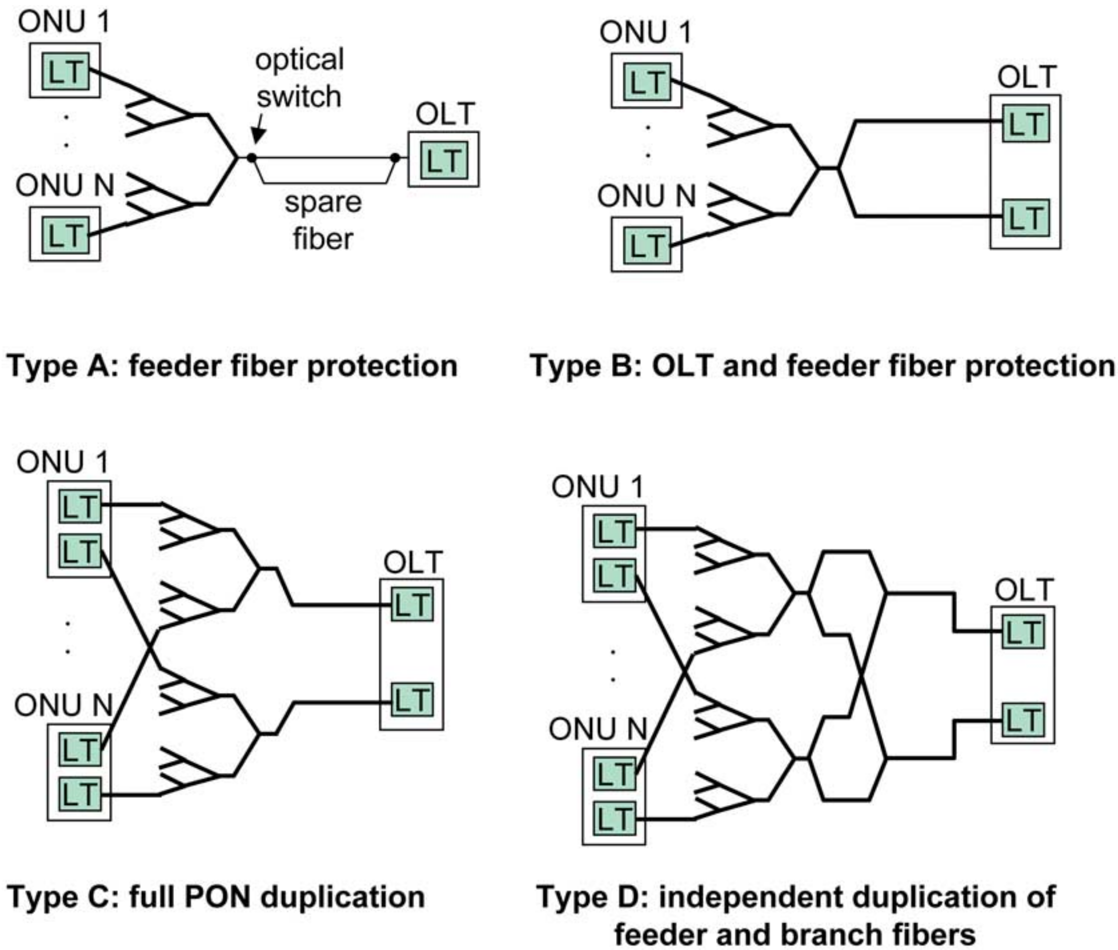

Fig. 7. *PON protection schemes.*

mode receiver at the OLT should therefore have a wide dynamic range, and should be able to set its decision threshold quickly to the appropriate level to discriminate the logical ones from the zeros. Also the power of the ONU transmitter can be varied over a certain range to limit the requirements on the receiver dynamic range. In this amplitude ranging process, the overhead to each ATM cell is used for supporting the fast decision threshold setting at the OLT burst mode receiver and the power adaptation at the ONU burst mode transmitter.

2) Network Protection: The long feeder line in a PON is a vulnerable part of the network; when unprotected, a break of it puts the whole PON out of service. Four types of network protection have been described in ITU-T Recommendation G.983.1 [9], as shown in Fig. 7. Type A protection involves protection of the feeder fiber only by a spare fiber over which the traffic can be rerouted by means of optical switches. After detection of a failure in the primary fiber and switch-over to the spare fiber, also reranging has to be done by the PON transmission convergence (TC) layer. Thus, only limited protection of the system is realized. Mechanical optical switches are used up to now; when optical switching becomes cheaper, this protection scheme may become more attractive. Type B protection features duplication of both the feeder fiber and the OLT. The secondary OLT is on cold standby, and is activated when the primary one fails. Due to the high sharing factor of the duplicated resources by the ONU-s, this approach offers an economical yet limited protection. Type C protection implies full duplication of the PON, and all equipment is normally working which allows fast switch-over (within 50 ms) from the primary equipment to the secondary one. The branch fibers as well as the ONU-s are protected; also a mix of protected and unprotected ONU-s can be handled. Type D protection features independent duplication of the feeder fibers and the branch fibers. It cannot offer fast restoration. It is less attractive than C, as it requires more components but not a better functionality. In summary, types B and C are the most attractive schemes for PON protection.

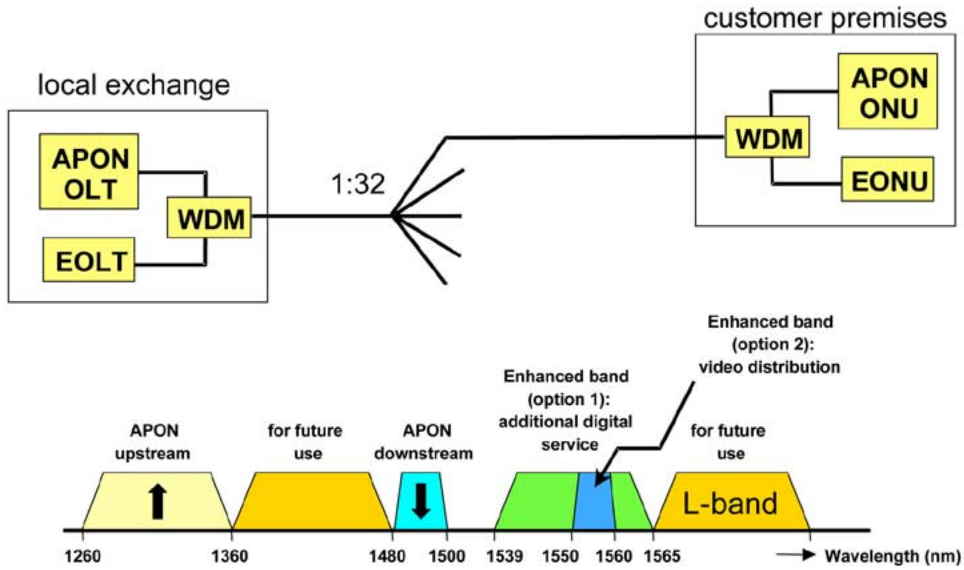

Fig. 8. ***WDM enhancement G.983.3.***

3) Extensions of ATM PON: To further increase the speeds laid down in Recommendation G.983.1, research has been done into 622-, 1244-, and 2488-Mbit/s line rates, both for upstream and downstream. A key technical issue is the development of faster burst-mode circuitry to adequately retrieve the timing and set the decision threshold level, which becomes increasingly more difficult at higher line rates. Operation of 1244-Mbit/s burst-mode circuitry has been achieved [10]. In January 2003, ITU has set standards for gigabit-capable PONs (G-PONs) in the G.984 series, which may operate at downstream speeds and upstream speeds up to 2.5 Gbit/s; see Section IV-C.

The G.983.1 ATM PON was initially mainly designed for high-speed data communication. However, in the residential access networks there is also a clear demand for economical delivery of CATV services, for which subcarrier multiplexing techniques are quite appropriate. In the enhanced Recommendation G.983.3 [9], room has been allocated in the optical spectrum to host video services or additional digital services next to the ATM PON services. As shown in Fig. 8, the APON upstream services remain in the 1260–1360 nm band (as in G.983.1), but the band for downstream services is narrowed to 1480–1500 nm (1480–1580 nm in G.983.1). Next to those, an enhancement band for densely wavelength multiplexed bidirectional digital services (such as private wavelength services) is foreseen, or an enhancement band for an overlay of video delivery services. The latter is used in downstream direction only, and coincides with the *C*-band as thus economical erbium-doped fiber amplifiers can be deployed for the power boosting required. When positioning an overlay of CATV distributive services in the *C*-band, stringent crosstalk requirements have to be put on the wavelength multiplexers and demultiplexers, to prevent noticeable interference of the CATV signals into the digital ATM signals, and *vice versa* [11].

In order to further improve the economics of ATM PON systems, an extended PON system with an increase of the network splitting factor to 128 and even 256 has been developed, while still maintaining a passive outside plant and compatibility with G.983.1 compliant ONU-s [12]. This extended split is achieved by a larger optical power budget. In the downstream direction, at the OLT a high power laser diode or an erbium-doped fiber amplifier (EDFA) is used to boost the power. In the upstream direction, the sensitivity of the burst-mode receiver is improved by applying an avalanche photo diode (APD). Also 8 single-mode feeder fibers (each feeding a 1 : 16 or 1 : 32 power splitter in the field) are at the OLT coupled to a multimode fiber yielding a low-loss coupling to the receiver.

Even further extensions of the split factor and of the reach of an ATM PON have been realized in the SuperPON system [13]. An extension to a splitting factor of 1 : 2048 has been achieved; this needs, however, active equipment in the field. In the downstream direction exploiting the 1530–1560 nm wavelength window, EDFA-s are used for overcoming the large path losses. In the upstream direction, gated semiconductor optical amplifiers (SOA-s) are deployed. Each SOA gate is opened when upstream packets arrive, and is shut otherwise in order to avoid funneling of the amplified spontaneous emission noise toward the OLT. This SuperPON approach is not compliant with current standards, and may be economically feasible only in the long term [12].

Recently, an other long-reach PON concept has been demonstrated [14], having a reach up to 100 km and

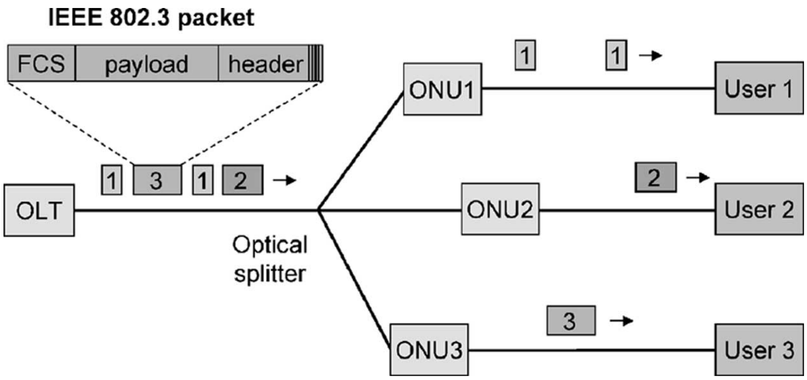

Fig. 9. *Downstream traffic in an EPON.*

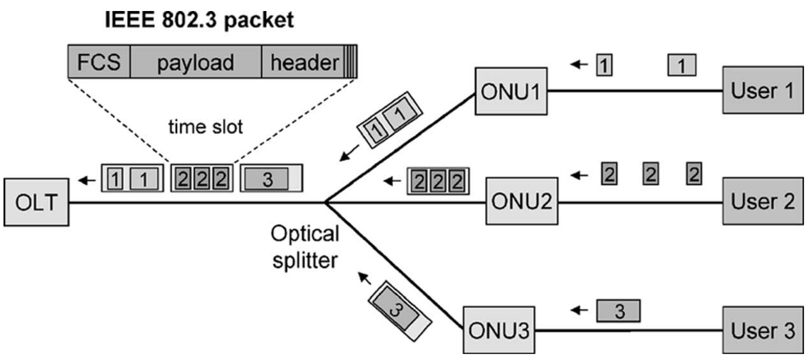

Fig. 10. *Upstream traffic in an EPON.*

addressing 500–1000 ONU-s with an aggregate symmetrical capacity of 2.5 or 10 Gbit/s using forward error correction (FEC). Such a long reach and high split factor would allow the bypassing of many local exchanges, thus saving a lot on backhaul costs. EDFA-s (without gating) are needed to overcome the splitting losses, and wavelength multiplexing may be used for providing adequate capacity to network parts ("wavelength to the street corner").

B. Ethernet PON

With the rapid penetration of Ethernet-based services, EPON techniques are receiving increasing attention, and are promoted by the IEEE 802.3ah Ethernet in the First Mile (EFM) Task Force [15]. The major difference with ATM PON-s is that an EPON can carry variable-length packets up to 1518 bytes in length, whereas an ATM PON carries fixed-length 53-byte cells. This ability yields a higher efficiency for handling IP traffic. The packets are transported at the gigabit Ethernet 1.25-Gbit/s speed using the IEEE 802.3 Ethernet protocol. A well-designed medium access control (MAC) protocol is needed, a.o. for bandwidth allocation and to support a variety of services having different quality-of-service requirements [16].

The EPON features full-duplex transmission similarly as the ATM PON, with downstream traffic at 1490 or 1510 nm, and upstream traffic at around 1310 nm. As shown in Fig. 9, standard IEEE 802.3 Ethernet packets are broadcasted downstream by the OLT to all the ONU-s. Each ONU inspects the headers, and extracts the packets that are addressed to it. Several variable-length packets are put into a fixed-length frame of typically 2 ms duration, and each frame begins with a 1-byte synchronization marker. In the upstream direction, also 2 ms frames are used. A frame contains time slots that each are assigned to one of the ONU-s (see Fig. 10). Each ONU puts one or more of its upstream variable-length IEEE 802.3 packet into a time slot; if it has no packets to send, the time slot may be filled with an idle signal. No packet fragmentation takes place. The time slot overhead consists of a guard band and indicators for timing and signal power. The OLT thus allows only one ONU to send at a time, and no collisions occur. The time slot size typically is 125 or 250 μs. The frame duration and time slot size are not standardized by the IEEE 802.3ah EFM Task Force. The values mentioned are typical examples; they depend on quality-of-service requirements such as latency and guaranteed bandwidth.

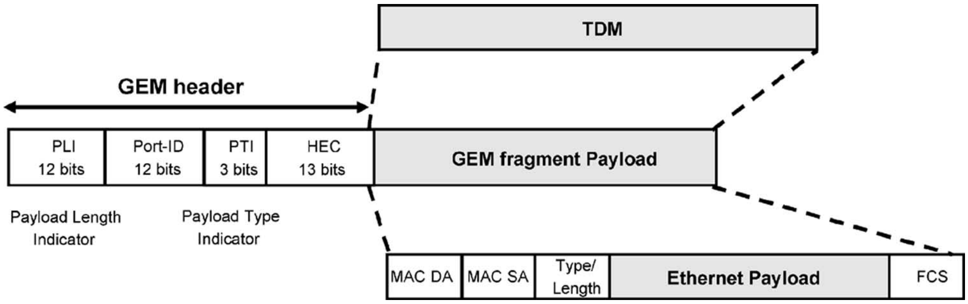

Fig. 11. *GPON encapsulation method according to ITU-T Rec. G.984.3.*

C. Gigabit PON

In order to extend the capacity of PONs into the Gbit/s arena, the ITU has set standards for the GPON in the G.984.x series. The GPON architecture, set in Recommendation G.984.1, is much alike the ATM PON one: the maximum optical splitting ratio is 128, and the maximum fiber reach from OLT to ONU is 20 km whereas its minimum is zero. Protection schemes have also been foreseen, similar to those shown in Fig. 7.

The GPON physical media dependent layer has been set in G.984.2; it includes downstream line rates of 1244.16 or 2488.32 Mbit/s, in the wavelength range 1480–1500 nm. In upstream direction, line rates foreseen are 155.52, 622.08, 1244.16, or 2488.32 Mbit/s, in the wavelength range 1260–1360 nm.

In GPON Transmission Convergence Recommendation G.984.3, a framing format of 125-μs length is used which can host a lot of different packetized traffic formats. This GPON encapsulation method (GEM) may host Ethernet packets, and/or native ATM packets, and/or native TDM, as illustrated in Fig. 11 [17], [18]. Thus, a GPON system may operate in an Ethernet-packet-only mode, or in an ATM-only mode, or in a mixed mode. Ethernet frames may be fragmented among a number of GEM cells, which is not possible in the native IEEE 802.3 technology. Hence, GPON using GEM can obtain a high efficiency for transport of IP data payload, by utilizing up to 95% of the available bandwidth in the transmission channel.

GPON also supports quality of service, as it enables service level agreement (SLA) negotiations between the OLT and the ONU through the ONU management and configuration interface set in G.984.4.

D. Comparison of TDMA Systems

By using ATM techniques, ATM PON offers built-in quality of service for all traffic classes, whereas EPON through using native Ethernet may not, unless the QoS is managed at the IP level. EPON in its basic form thus may not support voice services with QoS as provided in the traditional public switched telephone network (PSTN), and also the support of real-time services still has issues due to latency and packet jitter; advanced MAC protocols may reduce these shortcomings. On the other hand, ATM suffers from the cell tax (5-byte header per 53-byte cell), and thus EPON is more efficient and simple for transporting variable length IP packets. The recently introduced GPON can carry ATM as well as Ethernet traffic in any mixed mode, with high efficiency, and hence may combine the quality-of-service advantages of ATM nicely with the efficiency of Ethernet.

V. HYBRID FIBER COAX NETWORKS

CATV networks usually are laid out over large geographical areas, and are mainly designed for downstream broadcasting of analog TV channels (or digital TV channels, multiples of which fit into one analog TV channel frequency slot). These channels are frequency-division multiplexed in a carrier frequency grid extending up to 1 GHz. In traditional all-coax CATV networks, in the trunk part amplifiers were typically required every 600 m, and there were 20–40 amplifiers in cascade. During transmission in the coaxial cable network, the signal quality deteriorates due to the addition of noise from the electrical amplifiers and intermodulation products caused by their nonlinearities. In a hybrid fiber coax (HFC) system, as shown in Fig. 12, low-loss fiber is used in the trunk part, and the trunk amplifiers are eliminated [19]. This improves the signal quality, and reduces maintenance costs. The CATV headend station is collecting the CATV signals, remodulating them into a specific frequency grid, and sending them via single-mode fibers to fiber nodes. Each fiber node converts the composite optical signal into an electrical one, which is carried via a coaxial cable network including a few (typically four to six) RF amplifiers to the residential homes. A single headend may thus serve hundred thousands of customers, and a fiber node some thousands of customers.

In the fiber part of the HFC network, the signals are carried with subcarrier multiplexing; see Fig. 13. The TV channels are each amplitude-modulated on a separate frequency. After summing all these modulated signals, the composite CATV signal is modulating the intensity of the

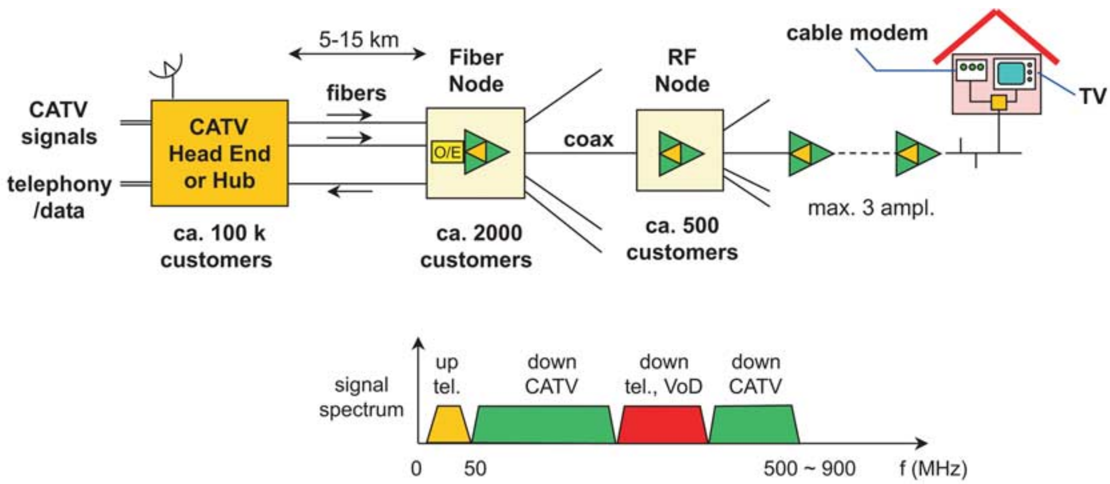

Fig. 12. ***Hybrid fiber coax network.***

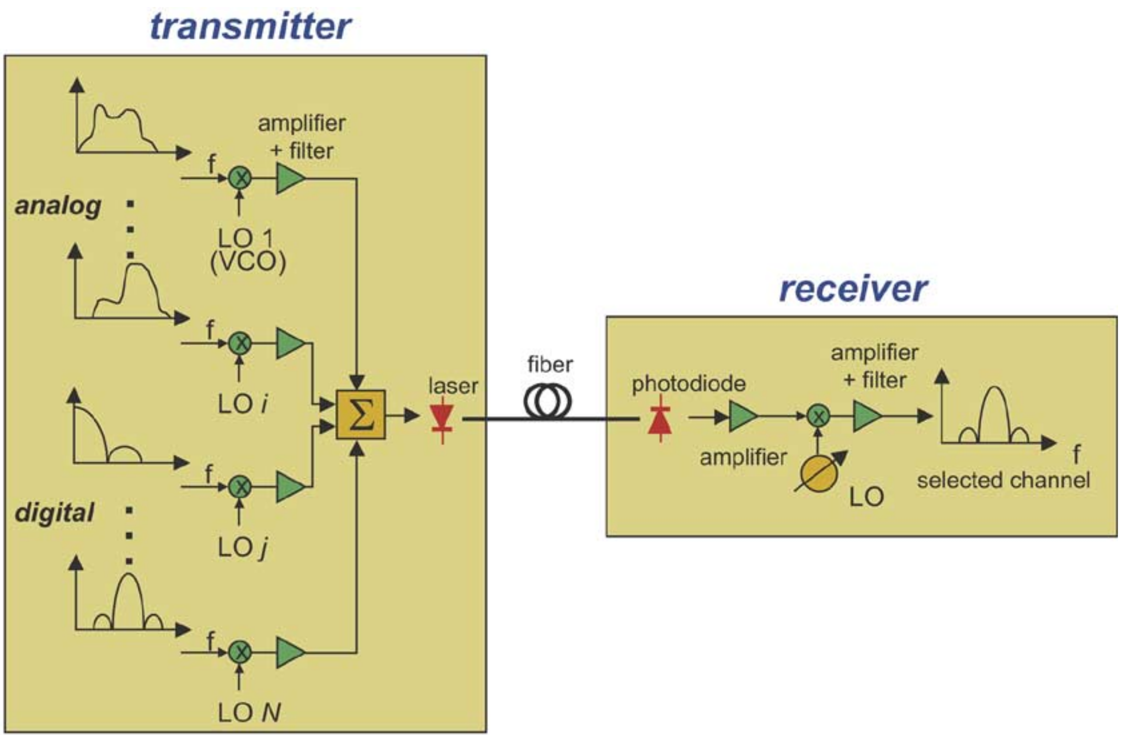

Fig. 13. ***Subcarrier multiplexing.***

light output of a highly linear high power laser diode (or laser diode followed by a linearized external modulator). At the receiver in the fiber node, the optical signal is converted backward into the composite electrical CATV signal by means of a highly linear PIN photodiode plus subsequent electrical amplifying stages. Thereafter the signal can be passed to the coaxial cable network. When using a laser diode with low relative intensity noise and high linearity (or a carefully linearized external modulator), the CATV signal can be transported with very little loss of quality. If a 1.5 μm wavelength laser diode is used, erbium-doped fiber amplifiers may boost the power at the headend and compensate for the splitting losses in the fiber network; thus very extensive networks feeding thousands of ONU-s can be realized. In this wavelength region, however, with direct laser modulation second order intermodulation products may arise due to laser chirp in combination with fiber chromatic dispersion. With an external modulator, however, the chirp is small enough to avoid these intermodulation products. When a 1.3-μm wavelength laser diode is used, the fiber chromatic dispersion is sufficiently small to eliminate these products as well; however, there do not exist such efficient optical amplifiers for this wavelength region, and hence less extensive networks can be realized.

The CATV signal quality that can be maintained in HFC networks is very high due to the fiber's low losses and high bandwidth in comparison with coaxial cable. Therefore, in HFC networks fiber is gradually brought deeper into the network, and fiber nodes have to serve fewer customers through a coaxial cable network of limited size (i.e., minifiber nodes, each serving in the order of 40 customers).

HFC networks are nowadays not only carrying CATV and FM radio broadcast services, but cable operators are also exploiting them for voice telephony and data transport using cable modems in a so-called triple-play scenario. The associated upstream traffic is carried in SCMA mode, and can deploy parts of the spectrum unused for CATV and FM radio broadcast. In Europe, typically the 5–65 MHz band is used for this; in the United States, the 5–42-MHz range. For downstream data, e.g., the 300–450-MHz range is used, taking into account that Internet traffic is usually highly asymmetric (much more downloading of data than uploading). Downstream per 8-MHz CATV channel, 30–50-Mbit/s data can be accommodated deploying 64 or even 256 quadrature amplitude modulation (QAM). For upstream data transport, due to ingress noise less comprehensive modulation schemes are to be used; e.g., DQPSK, which offers about 3 Mbit/s per channel.

VI. DENSE WAVELENGTH MULTIPLEXING IN ACCESS NETWORKS

The rapid growth in access network traffic asks for powerful measures to increase the capacity of the infrastructure. An installed fiber plant can effciently be upgraded to higher capacities, while protecting the infrastructure investments made, by introducing multiple wavelength channels in the same fiber infrastructure. In the static WDM-PON concept, discussed in Section III-C, each ONU is connected by a specific wavelength pair to the OLT in a point-to-point fashion. By assigning the wavelengths dynamically to the ONUs, e.g., by flexible wavelength routing, the access network capabilities can be significantly enhanced [20]–[22]. This dynamic WDM-PON concept has not reached commercial deployment yet, but is a promising topic for research into future access network techniques.

A. Role of Multiwavelength Techniques

By creating multiple wavelengths in a common fiber infrastructure, the capabilities of this infrastructure can be extended into an additional dimension. This wavelength dimension may implement independent communication planes between nodes, thus enabling versatile interconnection patterns between nodes. E.g., these interconnections can be asynchronous, can have different quality-of-service requirements, and can transport signals with widely differing characteristics. This has some similarity with the enhanced interconnection possibilities of multilayer printed circuit boards.

The role of this wavelength dimension can be manifold, such as:

- to separate services;
- to separate service providers;
- to enable traffic rerouting;
- to provide higher capacity;
- to serve more users (improved scalability).

Also the assignment of the wavelength channels may follow different scenarios:

- static allocation;
- semistatic allocation;
- dynamic allocation.

Each of the above-mentioned roles may follow one or more of the scenarios. In the following, each of the roles will be considered in more detail.

1) Service Separation: By allocating a wavelength (or a set of wavelengths) for a cohesive set of services, these services may be separated by means of their wavelength. This may be beneficial for treating a set of services with similar quality-of-service requirements and signal characteristics in a dedicated way. E.g., bidirectional multimedia services may have specific requirements for latency and bandwidth, and hosting these in one or more specific wavelength channels with their dedicated routing patterns may help for supporting these requirements. In a point-to-multipoint architecture, by using wavelength routing a lower split factor may be implemented for services with high bandwidth requirements, whereas other services may get higher split factors.

Separating services on a wavelength basis may also help to realize different tariff structures by the network operator: traffic traveling on the first-priority (e.g., guaranteed congestion-free) wavelength channel may be charged a higher fee than on lower priority channels.

2) Service Provider Separation: Wavelength channels may also be dedicated to service providers. They thus get each their virtually independent infrastructure, on which they can guarantee their own basket of services and pertaining quality of service. It also enables flexible leasing of network capacity by the network operator, who may assign a certain set of wavelength channels for a certain region for a certain period to a specific service provider, and charge

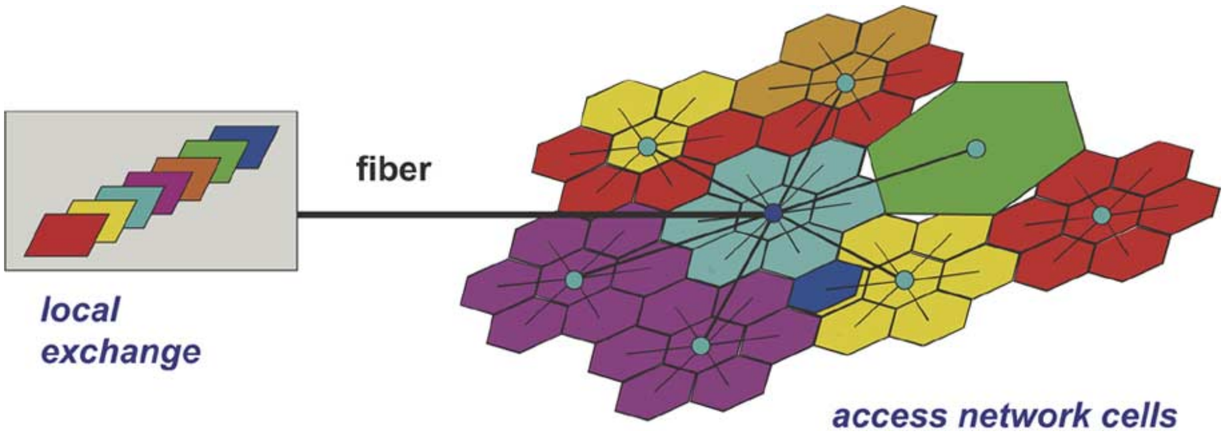

Fig. 14. *Reallocating wavelength channels.*

him for that. By rerouting the wavelength channels the network operator can easily change these leasing conditions. When a user subscribes to a particular service provider, he may get the corresponding wavelength channel(s) and thus transparently the services involved.

In case of several competing service providers in the same region, these providers may thus coexist in the same network infrastructure independently.

3) Traffic Rerouting: Using multiple wavelength channels serving different regions, each wavelength channel or set of wavelength channels may feed a dedicated region. Such a region may encompass one or more ONUs. For instance, in a static WDM-PON, each ONU is connected to the OLT by a specific pair of wavelengths. When operating in networks with diversity in fiber links (e.g., in a mesh network in which various fiber paths can be followed to establish a connection between two nodes), wavelength-specific routing actually ties wavelengths to regions. By changing the wavelength routing, this "coloring" can easily be changed. For instance, when a specific fiber link feeding a region fails and the traffic carried through the wavelength channels on it is disrupted, by steering the wavelength channel(s) via alternative fiber paths the traffic provisioning to that region may be quickly restored.

Also when a link feeding a certain region gets congested, and no extra wavelength channels can be added on that link, these extra channels may be routed via alternative fiber links to the same region, thus resolving the congestion problem.

4) Higher Capacity: Adding wavelength channels on a fiber link may also be done just to increase the capacity on the link, by creating several channels in parallel carrying the same type of traffic. This implies, for example, that more of the same services may be offered. To get access to those services, however, the end user needs to be retuned to that wavelength channel.

B. Wavelength Channel Assignment Scenarios

Wavelength channels may be assigned to end users on different time scales, depending on the service operator or network operator requirements. Basically, this may be seen as "coloring the network," on a slow or fast time scale. Fig. 14 illustrates the principle: from the OLT-s in the local exchange, multiple wavelength channels are fed to the ONU-s in the regional user cells via a tree-and-branch PON. By wavelength-selective routing in the PON, or wavelength selection at each ONU, each wavelength channel can be assigned to one or more ONU-s. Thus, capacity can be specifically shared between these ONU-s. The ONU-s subsequently transfer these capacity shares to the end users (possibly via an electrical last drop to the end user, being wired or wireless).

The mapping of the network capacity resources to the end users (or their local networks) can thus be changed by changing the wavelength channel assignment. Basically two approaches can be followed for this, as illustrated in Fig. 15: wavelength selection at the ONU-s, or a wavelength routing in the field.

In the *wavelength selection* approach shown in Fig. 15(a), all wavelength channels are broadcasted to every ONU, and subsequently the ONU is tuned to the wavelength channel wanted. Clearly the power of the other wavelength channels is wasted at the ONU, and losses at the broadcasting power splitter are significant. An optical amplifier is usually needed to make up for these losses; the amplifier needs to operate bidirectionally to handle downstream as well as upstream traffic. No specific provisions in the network are needed for supporting broadcast services. However, for privacy protection special measures are needed to prevent illegal

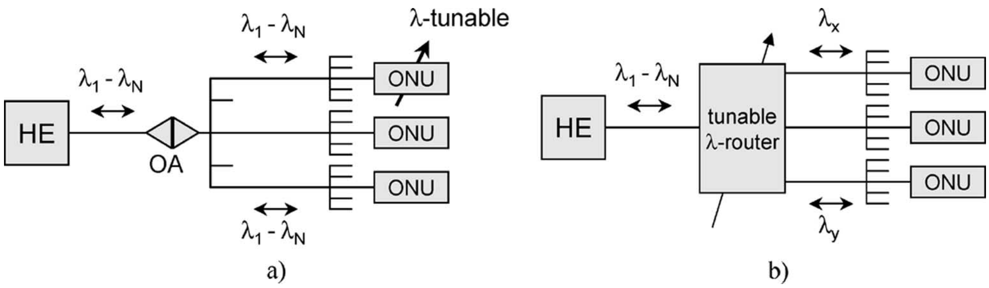

Fig. 15. *Dynamically allocating wavelength channels to ONU-s. (a) Broadcast-and-select. (b) Flexible wavelength routing.*

tuning by the end user of an ONU to a not-allowed channel. An implementation example of this approach is given in Section VI-C.

In the *wavelength routing* approach shown in Fig. 15(b), a wavelength router in the field directs the wavelength channels to specific output ports. In the static WDM PON, this router has a fixed wavelength routing scheme. When the router is tunable, the routing may be dynamically adjusted by external control signals from the local exchange. In order to support the delivery of broadcast services to all ONU-s as well, extra provisions have to be made for enabling broadcast wavelength channel(s) to bypass the router. As the wavelength channels are routed to only those ONU-s whose customers require and are allowed to get the associated services, no optical power nor data capacity resources are wasted and privacy issues are avoided. An implementation example of this approach is given in Section VI-D.

C. Wavelength Broadcast-and-Select Access Network

Fig. 16 presents a multiwavelength overlay of a number of ATM PON networks on a HFC network, following the *wavelength channel selection* approach [21]. Fig. 16(a) shows a fiber-coax network for distribution of CATV services, operating at a wavelength λ_0 in the 1550–1560 nm window where erbium-doped fiber amplifiers (EDFA-s) offer their best output power performance. Thus, using several EDFA-s in cascade, an extensive optical network splitting factor can be realized and a large number of customers can be served. For example, with two optical amplifier stages and typical splitting factors of $N = 4$ and $P = 16$, and a minifiber node serving 40 users via its coaxial network, a total of 2560 users is served from a single headend fiber. For interactive services, the upstream frequency band in a standard HFC network (with a width of some 40–60 MHz) has to be shared among these users, thus limiting the bitrate per user to narrowband services such as voice telephony.

An upgrade of the system in order to provide broadband interactive services can be realized by overlaying the HFC network with a number of wavelength-multiplexed bidirectional data systems. In the ACTS TOBASCO project [21], such an overlay was made with four APON systems; see Fig. 16(b) Four APON OLT-s at the headend site are providing each bidirectional 622-Mbit/s ATM signals on a specific downstream and upstream wavelength. These eight wavelengths are positioned in the 1535–1541-nm window, where the up- and downstream wavelength channels are interleaved with 100-GHz spacing. The APON wavelengths are combined by a high-density wavelength division multiplexer (HDWDM), and subsequently multiplexed with the CATV signal by means of a simple coarse wavelength multiplexer (thanks to the wide spacing between the band of APON wavelengths and the CATV wavelength band). The system upgrade implies also replacement of the unidirectional optical erbium-doped fiber amplifiers by bidirectional ones which feature low noise high-power operation for the downstream CATV signal, and for the bidirectional ATM signals a wavelength-flattened gain curve plus a nonsaturated behavior (to suppress crosstalk in burst-mode). At the ONU site, first the CATV signal is separated from the APON signals by means of a coarse wavelength multiplexer, and is subsequently converted to an electrical CATV signal by a highly linear receiver and distributed to the users via the coaxial network. The APON signals are fed to a wavelength-switched transceiver, of which the receiver can be switched to any of the four downstream wavelength channels, and the transmitter to any of the four upstream ones. The wavelength-switched transceiver may be implemented by an array of wavelength-specific transmitters and receivers, which can be individually switched on and off; this configuration allows to set up a new wavelength channel before breaking down the old one ("make-before-break"). Alternatively, it may use wavelength-tunable transmitters and receivers, which can in principle address any wavelength in a certain range; this eases further upgrading of the system by introducing more wavelength channels, but also implies a "break-before-make" channel switching. The network management and control system commands to which downstream and to which upstream wavelength channel each ONU transceiver is switched. By issuing these commands from the headend station, the network operator actually

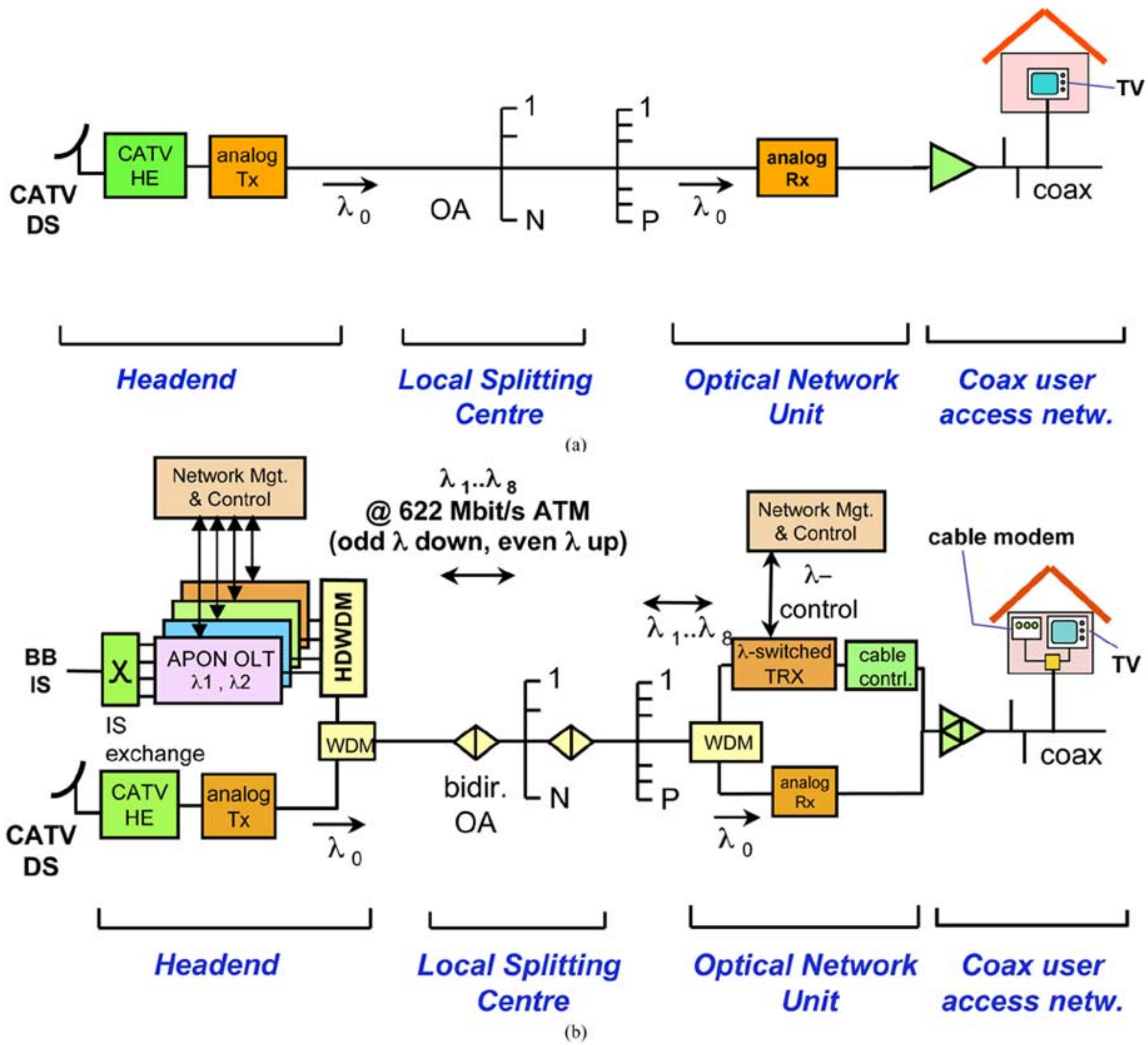

Fig. 16. ***Flexible capacity assignment in a multiwavelength fiber-coax network by wavelength selection at the ONU-s. (a) Fiber-coax network for distribution of CATV services. (b) Upgrading of the fiber-coax network with multiwavelength APON system for delivery of broadband interactive services.***

controls the virtual topology of the network, and thus is able to allocate the network's capacity resources in response to the traffic demands at the various ONU sites. The network management command signals are transported via an out-of-band wavelength channel in the 1.3-μm wavelength window. The APON signals channel selected by the ONU is converted into a bidirectional electrical broadband data signal by the transceiver, which is by a cable modem controller put in appropriate frequency band for multiplexing with the electrical CATV signal. The upstream data signal is usually put below the lowest frequency CATV signal (so below 40–50 MHz), and the downstream signal in empty frequency bands between the CATV broadcast channels. The signals are carried by the coaxial network (in which only the electrical amplifiers need to be adapted to handle the broadband data signals) to the customer homes, where the CATV signal is separated from the bidirectional data signals; the latter signals are processed by a cable modem, which interacts with the cable modem controller at the ONU site. This system has been successfully deployed in a field trial [21].

By remotely changing the wavelength selection at the ONU-s, the network operator can adjust the system's capacity allocation in order to meet the local traffic demands at the ONU sites. As illustrated in Fig. 17, the ONU-s are allocated to the four upstream (and downstream) wavelength channels, which each have a

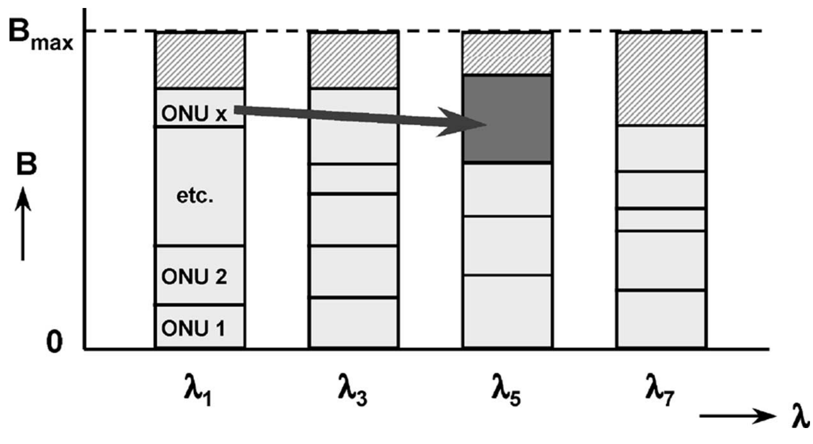

Fig. 17. *Reallocating ONU-s to wavelength channels.*

maximum capacity of 622 Mbit/s for ATM data. As soon as the traffic to be sent upstream by an ONU grows and does not fit anymore within its wavelength channel, the network management system can command the ONU to be allocated to an other wavelength channel, in which still sufficient free capacity is available. Obviously, this dynamic wavelength reallocation process reduces the system's blocking probability, i.e., it allows the system to handle more traffic without blocking and thus it can increase the revenues of the operator for a given pool of communication resources at the local exchange.

D. Wavelength Routing Access Network

The WDM-PON concept (see Fig. 5) deploys *static wavelength channel routing* in the PON splitting point, e.g., by an arrayed waveguide router. Each ONU is connected to the OLT by a specific pair of wavelengths, which may be spaced by the periodicity of the waveguide router (its free spectral range). Thus, a logical point-to-point connection is emulated between each ONU and the OLT, on a physical point-to-multipoint infrastructure. Hence, no multiple access protocol is needed. The data capacity and the service offerings may be set per individual ONU, which enables easy per-ONU upgrading and scaling. No capacity is shared among the ONUs, so no statistical multiplexing gains can be achieved. As discussed in Section III-C, deploying colorless ONUs may yield cost-effective WDM-PON solutions. An example of such a system concept deploying reflective SOAs is shown in Fig. 18 [5]. The continuous-wave optical carriers to be modulated with data by the reflective SOAs are all located at the local exchange; they may be generated by an array of DFB laser diodes, or be extracted from the amplified spontaneous emission of an erbium-doped fiber amplifier. This approach yields a universal source-free and wavelength-agnostic ONU.

Fig. 19 presents how the *dynamic wavelength channel routing* approach may be deployed in a fiber-wireless network in order to allocate flexibly the capacity of a number of ATM PON point-to-multipoint systems among ONU-s in a single fiber split network infrastructure [22]. The ONU-s are each feeding a radio access point (RAP) of e.g., a wireless LAN, which connects to a variable number of users with mobile terminals. These users move across the geographical area served by the network (e.g., a business park, airport departure lounge, etc.), and they may want to set up a broadband wireless connection to their laptop at any time anywhere in this area. When many users are within a wireless cell served by a certain RAP, this cell may have to handle much more traffic than the other cells; it has become a "hot spot" which has to be equipped with additional capacity. The corresponding RAP may switch on more microwave carriers to provide this additional capacity over the air, and also has to claim more capacity from the ONU. This local extra capacity can be provided by reallocation of the wavelength channels over the ONU-s, which is done by a flexible wavelength router positioned in the field. Similar to the architecture of the wavelength-reconfigurable fiber-coax network in Fig. 16(b), the architecture in Fig. 19 developed in the ACTS PRISMA project [21] has four 622 Mbit/s bidirectional APON OLT-s with a specific downstream wavelength and an upstream one each. The four downstream wavelengths are located in the 1538–1541-nm range, with 100-GHz spacing, and the four upstream ones in the 1547–1550-nm range with the same spacing. The flexible wavelength router directs the downstream wavelength channels each to one or more of its output ports, and thus via a split network to a subset of ONU-s. The RAP-s could operate with up to five microwave carriers in the 5-GHz region, each carrying up to 20-Mbit/s ATM wireless LAN data in orthogonal frequency division multiplexing (OFDM) format. At the flexible router (or at the local exchange) a number of continuous-wave emitting laser diodes are located, which provide unmodulated light power at the upstream wavelengths. The flexible router

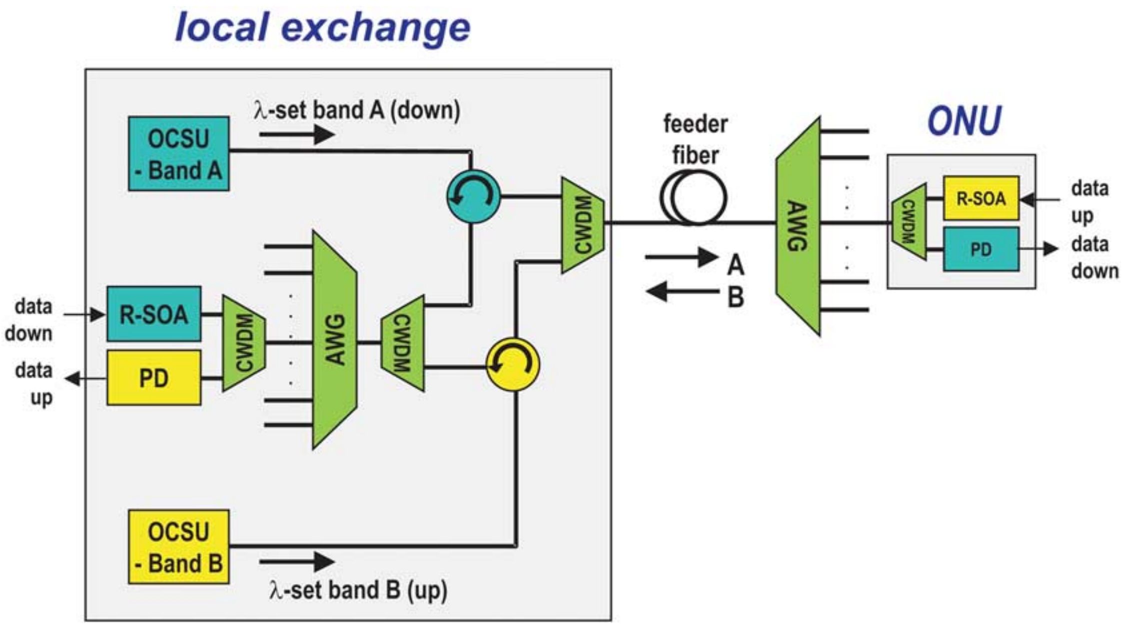

Fig. 18. *WDM-PON with colorless ONUs deploying reflective semiconductor amplifiers (OCSU: optical carrier supply unit).*

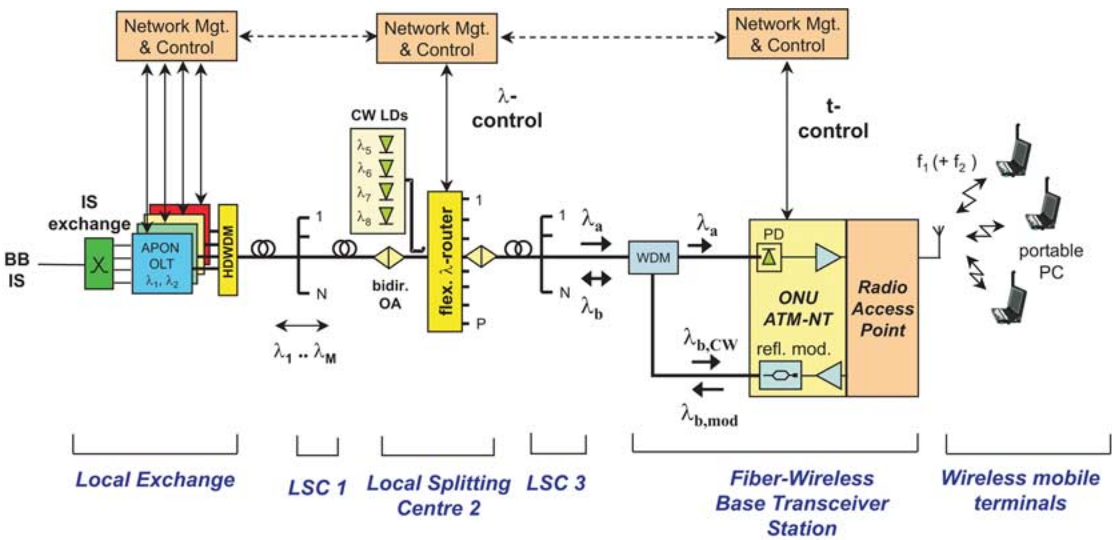

Fig. 19. *Flexible capacity assignment in a multiwavelength fiber-wireless network by wavelength routing in the field.*

can select one of these upstream wavelengths, and direct it to the ONU-s that can modulate the signal with the upstream data and return it by means of a reflective modulator via the router to the local exchange. Thus, no wavelength-specific source is needed at the ONU, the downstream light sources are shared by a number of ONU-s, and all ONU-s are identical, which reduces the system costs and the inventory issues. The flexible wavelength router can be implemented with a wavelength demultiplexer separating the wavelength channels, followed by power splitters, optical switches and power couplers in order to guide the channels to the selected output port(s). Depending on the granularity of the wavelength allocation process, the flexible router may be positioned at various splitting levels in the network.

Using a similar strategy to assign wavelength channels to the ONU-s as depicted in Fig. 17, a statistical performance analysis has been performed of the blocking probability of the system. It was assumed that the total network served 343 cells, of which 49 were "hot spots," i.e., generated a traffic load two times as large as a regular cell. It was also assumed that the system deployed seven wavelength channels, and that the calls arrived following a Poisson process where the call duration and length were uniformly distributed. Fig. 20 shows how the system blocking probability depends on the offered load (normalized on the total available capacity, which is 7 times 622 Mbit/s), using various system architecture options. In the static WDM case (i.e., when wavelength reallocation is not possible) where all the 49 hot spots are served by ONU-s assigned to the same wavelength channel, this obviously yields the worst-case blocking probability. On the other hand, in the static WDM case where the 49 hot spots were evenly spread over the seven wavelength channels, the blocking probability is much lower (i.e., best case). Unfortunately, a network operator cannot know beforehand where the hot spots will be positioned, so in an arbitary static WDM case the system blocking probability will be anywhere between the best case and the worst case, and no guarantee for a certain blocking performance can be given. When, however, dynamic reallocation of the wavelength channels is possible, the system can adapt to the actual hot spot distribution. Fig. 20 shows that when the flexible wavelength router is positioned at the second splitting point in the network, the blocking performance is better than the best-case static WDM performance; but more importantly, it is also stable against variations in the hot spot distribution, and thus would allow an operator to guarantee a certain system blocking performance while still optimizing the efficiency of his system's capacity resources. The blocking performance may be even better and more stable when positioning the flexible router at the third splitting point; however, this implies that the costs of the router are shared by less ONU-s. Locating the router at the second splitting point is considered to yield a good compromise between adequate improvement of the system blocking performance and system costs per ONU.

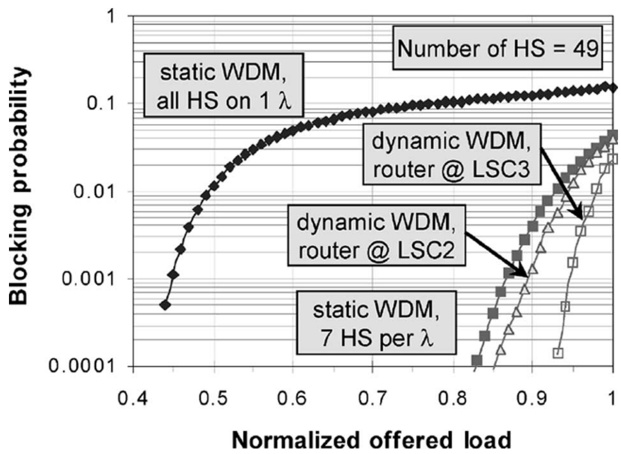

Fig. 20. *Improving the system performance by dynamic wavelength allocation.*

VII. RADIO OVER FIBER

Wireless communication services are steadily increasing their share of the telecommunication market. Next to their prime feature, mobility, they are offering growing bandwidths to the end users. This asks for smaller radio cells, and thus for higher radio carrier frequencies, which incur increased propagation losses and line-of-sight needs. Wireless LANs in the 2.4-GHz range according to the IEEE 802.11b standard carry up to 11 Mbit/s, and up to 54 Mbit/s in the IEEE 802.11g standard. The IEEE 802.11a and the HIPERLAN/2 standard provide up to 54 Mbit/s in the 5.4-GHz range. Research is ongoing in systems that may deliver more than 100 Mbit/s in the radio frequency range well above 10 GHz (e.g., LMDS at 28 GHz, HyperAccess at 17 GHz and 42 GHz, MVDS at 40 GHz, MBS at 60 GHz, etc.). Due to the shrinkage of radio cells at higher radio frequencies, ever more antenna sites are needed to cover a certain area such as the rooms in an office building, in a hospital, the departure lounges of an airport, etc. Thus, more RAPs are needed to serve e.g., all the rooms in an office building, and hence also a more extensive wired network is needed to feed these RAPs.

Instead of generating the microwave signals at each RAP individually, feeding the microwave signals from a central headend site to the RAPs enables to simplify the RAPs and thus to reduce their costs considerably. In this radio-over-fiber approach, the signal processing functions can be consolidated at the headend site, which allows more sophisticated signal processing, eases upgrading to new wireless standards. Thanks to its broadband characteristics, optical fiber is an excellent medium to bring the microwave signals to the RAPs.

A. Intensity Modulation/Direct Detection Systems

Radio over fiber systems using direct microwave intensity modulation of a laser diode are commercially available up to limited radio frequencies (up to about 2 GHz, for wireless services such as GSM and UMTS). The operation at higher microwave frequencies is prohibited by the restricted modulation bandwidth of the laser diode and by the fiber dispersion, which causes fading of the two modulation sidebands. Such microwave frequencies may only be handled by sophisticated very high frequency

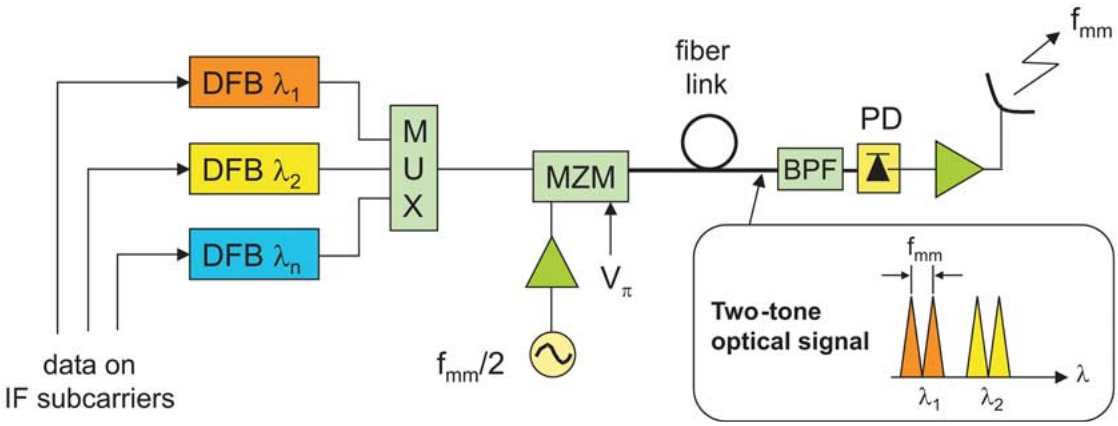

Fig. 21. *Generating microwave signals by heterodyning.*

optical analog transmitters and receivers, and careful fiber dispersion compensation techniques [23]. Operation at higher microwave frequencies may be more easily achieved by the advanced radio over fiber techniques being investigated in research laboratories, of which two examples are given in the next sections.

B. Heterodyning Systems

An attractive alternative avoiding the transport of multi-GHz intensity-modulated signals through the fiber is to apply heterodyning of two optical signals of which the difference in optical frequency (wavelength) corresponds to the microwave frequency. When one of these signals is intensity-modulated with the baseband data to be transported, and the other one is unmodulated, by optical heterodyning at the photodiode in the receiver the electrical microwave difference frequency signal is generated, amplitude-modulated with the data signal. This modulated microwave signal can via a simple amplifier be radiated by an antenna. Thus, a very simple low-cost radio access point can be realized, while the complicated signal processing is consolidated at the headend station.

This approach, however, requires two light sources with narrow spectral linewidth and carefully stabilized difference in optical emission frequency. An alternative approach requiring only a single optical source is shown in Fig. 21 [24]. The optical intensity-modulated signal from a laser diode is subsequently intensity-modulated by an external Mach–Zehnder modulator (MZM) which is biased at its inflexion point of the modulation characteristic and driven by a sinusoidal signal at half the microwave frequency. Thus, at the MZM's output port, a two-tone optical signal emerges, with a tone spacing equal to the microwave frequency. After heterodyning in a photodiode, the desired amplitude-modulated microwave signal is generated. The transmitter may also use multiple laser diodes, and thus a multiwavelength radio-over-fiber system can be realized with a (tunable) WDM filter to select the desired wavelength radio channel at the antenna site. The system is tolerant to fiber dispersion, and also the laser linewidth is not critical as laser phase noise is largely eliminated in the two-tone detection process.

C. Optical Frequency Multiplying Systems

An alternative approach to generate microwave signals by means of a different kind of remote optical processing, named *optical frequency multiplying (OFM)*, is shown in Fig. 22 [25], [26]. At the headend station the wavelength λ_0 of a tunable laser diode is swept periodically over a certain range $\Delta\lambda_{sw}$, with a sweep frequency f_{sw}. Alternatively, the wavelength-swept signal can be generated with a continuous-wave operating laser diode followed by an external phase modulator that is driven with the integral of the electrical sweep waveform. In a symmetrically driven Mach–Zehnder modulator, the intensity of the wavelength-swept signal is on/off modulated (with low frequency chirp) by the downstream data. After travelling through the fiber network, the signal transverses at the receiver an optical filter with a periodic bandpass characteristic. When the wavelength of the signal is swept back and forth over N filter transmission peaks, the light intensity impinging on the photodiode fluctuates at a frequency $2N \cdot f_{sw}$. Thus, the sweep frequency is multiplied, and a microwave signal with carrier frequency $f_{mm} = 2N \cdot f_{sw}$ plus higher harmonics is obtained. The intensity-modulated data is not affected by this multiplication process, and is maintained as the envelope of the microwave signal. The microwave signal is subsequently traversing an electrical bandpass filter (BPF) that rejects the unwanted microwave harmonics. Analysis and simulations have shown that the microwave signal is very pure; the inherent cancellation of the laser's optical phase noise makes that the spectral linewidth of the microwave signal is

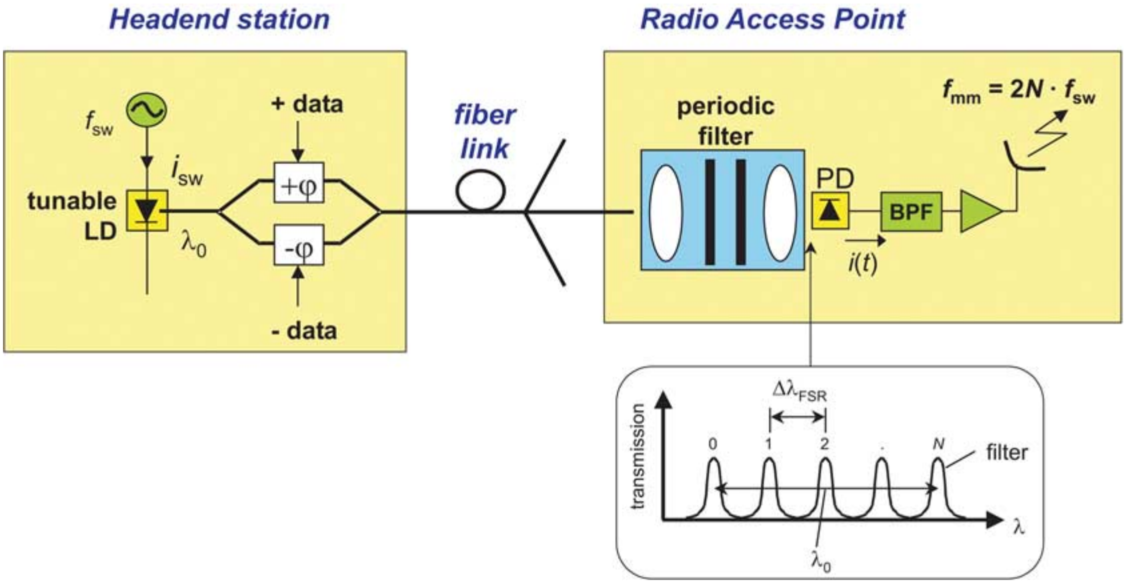

Fig. 22. *Generating microwave signals by optical frequency multiplying.*

much smaller than that of the laser diode [27]. Experiments have shown a microwave linewidth less than 50 Hz, whereas the laser linewidth exceeded 1 MHz [28]. The periodic optical bandpass filter can be advantageously implemented by a Fabry–Perót filter with a free spectral range $\Delta\lambda_{FSR}$ which is N times as small as the wavelength sweep range $\Delta\lambda_{sw}$. The microwave signal can also carry advanced data modulation schemes; e.g., simulations showed 16-level quadrature amplitude modulated (16-QAM) signals may be modulated on a subcarrier first, and then drive the Mach–Zehnder modulator. Experiments even showed successful transmission of 64-QAM signals at 17-GHz carrier frequency over 4-km multimode fiber [29].

The main advantage of this optical frequency multiplying method is that only relatively moderate sweep frequency signals are needed at the headend site (e.g., an f_{sw} up to 3 GHz), which can be generated with low phase noise, while at the antenna site low phase noise microwave signals with carrier frequencies in the tens of GHz region are generated. The system does not rely on heterodyning; it may operate also on multimode fiber networks (such as polymer optical fiber, which is easy to install inside buildings) by deploying the higher order passbands.

Assuming a linear behavior of the fiber, it can be shown that the periodic optical filter may also be positioned at the headend site (see Fig. 23), yielding the same optical frequency multiplication at the receiving end. Thus, the complexity of the antenna site is reduced further, and the characteristics of the filter can be readily tuned to the frequency sweep of the laser diode [27]. It also reduces costs further, as the filter may now be shared by several antenna sites.

The system can also transport upstream data from the antenna station to the headend. As illustrated in Fig. 23, by using a simple tunable local oscillator and a mixer, the microwave carrier generated at the antenna station by the optical frequency multiplying process can be downshifted, and be used for downconverting the upstream microwave signal from the mobile terminal to a tunable intermediate frequency (IF) [27]. This downconverted signal can subsequently be transmitted upstream on a separate wavelength by an IF-frequency optical transmitter.

D. Dynamically Allocating Radio Capacity

Wireless networks typically show considerable dynamics in traff ic load of the RAPs, due to the fluctuating density of mobile users in the radio cells. By allocating the network's communication resources to the RAPs according to their instantaneous traffic load, these resources can be more efficiently deployed, thus generating higher revenues. Fig. 24 illustrates how the OFM technique in combination with wavelength routing can yield such a dynamic capacity allocation [27]. At the central site, a number of frequency-swept sources each operating at a specific central wavelength are intensity-modulated by their respective downstream data streams. After wavelength multiplexing, a single periodic bandpass filter (i.c. an MZI) performs the OFM processing. The signals are injected into the ring network, where multicasting optical add–drop multiplexers (OADMs) can be tuned to drop one or more wavelength signals to an RAP.

The RAPs are wavelength-agnostic, and thus emit all the microwave signals carried by the dropped wavelength signals. Besides the electrical bandpass filter which has to

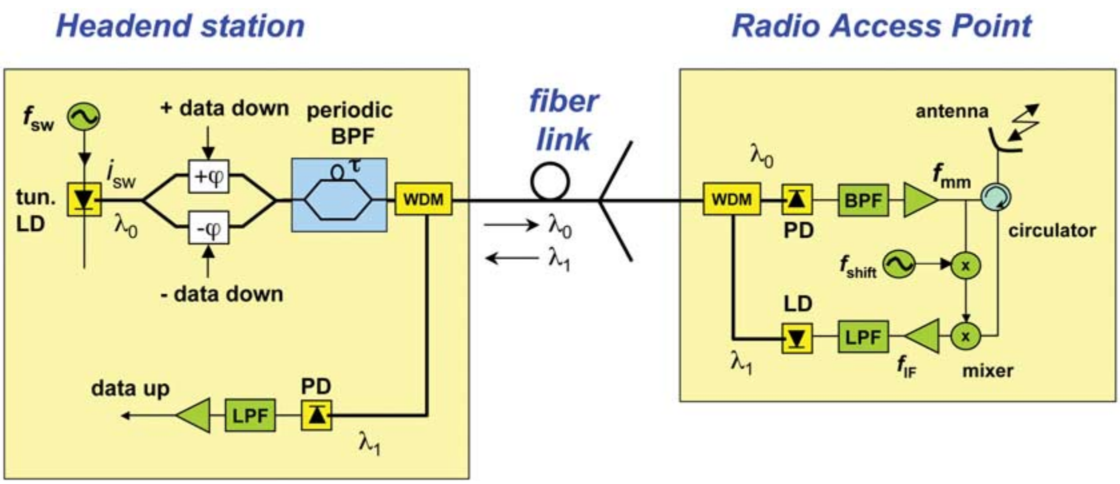

Fig. 23. *Bidirectional fiber-wireless system using optical frequency multiplying.*

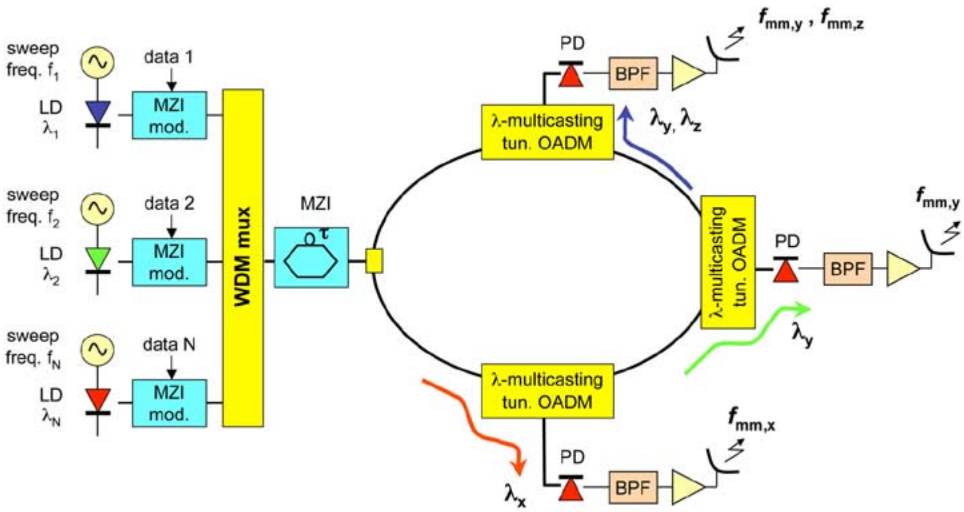

Fig. 24. *Flexibly allocating radio capacity in a radio-over-fiber system.*

select the desired microwave frequency, the RAP is also fairly frequency-independent. Therefore, this setup allows multistandard operation, in which the same RAP can handle a single microwave signal as well as multiple signals following different standards.

VIII. CONCLUDING REMARKS

The unique properties of low loss and huge bandwidth have made optical fiber the ideal communication medium in core and metropolitan networks, and are now also pushing fiber forward in the access network domain. Infrastructure costs are the major nut to crack here. Also, the costs of the OLT and ONU keep deserving attention. For short-reach access, point-to-point network topologies can be the most economical choice. For longer reaches, and if line termination issues in the local exchange become an issue, shared-feeder concepts such as the passive optical network tree-and-branch one can greatly reduce the installation and operation costs. This PON concept can support various multiple access techniques (among others, time-multiplexed access for ATM and Ethernet based traffic).

Next to its low loss and huge bandwidth, fiber offers a powerful extra dimension for networking, namely the wavelength domain. For example, by deploying wavelength multiplexing a shared-feeder WDM-PON may act as a virtual point-to-point topology. In the past, operators have invested a lot in various last-mile networks (e.g., twisted pair, coaxial cable) to reach their residential customers. In upgrading these networks to higher capacity and larger service variety, fiber may penetrate further toward the customer. It can support a wide range of last-mile technologies by hybrid combinations such as fiber-twisted pair, fiber-coax, and fiber-wireless. By means of adjustable wavelength routing techniques, the fiber feeder part of such hybrid networks can flexibly accommodate different operators and service categories. With dynamically adjustable wavelength routing, capacity-on-demand can be realized for efficient management of fluctuating traffic patterns, while respecting quality-of-service requirements.

Combining the huge bandwidth of fiber with the mobility offered by wireless communication makes fiber-wireless networks an attractive access scenario. By transporting the radio signals over fiber, the antenna sites of broadband wireless systems can be significantly simplified and thus system costs be reduced, whereas also more sophisticated signal processing (for e.g., antenna diversity systems) is facilitated. In combination with wavelength routing, powerful options for hot-spot handling can be devised.

IX. FUTURE PROSPECTS

The end user is still to benefit fully from all these ultrabroadband communication possibilities. Therefore, the optical fiber not only needs to reach up to his house, but needs to penetrate into it as well. It may reach close to his personal area network, which thanks to the ongoing miniaturization may consist of a myriad of small wireless power-lean terminals, sensors and actuators. These wireless devices may be incorporated not only in his residential living environment, but also in his clothes, his car, etc. Next to the traditional wired terminals such as the TV and desktop PC, these wireless devices may be connected to the fixed in-home and access network by a myriad of small intelligent antennas. Radio-over-fiber techniques, augmented with optical routing to accommodate dynamically the hot spots, may provide the best match of the ultimate capacity of fiber with the user freedom of wireless. Even in the wireless domain, optics may penetrate by means of intelligently steered free-space light beams providing the ultimate in wireless transport capacity.

Which in the far foreseeable future may make the communication world an end-to-end globally transparent one, with nearly unlimited communication capacity for anybody, anytime, anywhere, for any kind of service . . . the ultimate global crystal ball! ■

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