Fibre-optic techniques for broadband access networks

TON KOONEN

Ton Koonen is Professor at the COBRA Institute, Eindhoven University of Technology, The Netherlands

The fast growth in capacity demand in access networks, driven by the increasing thirst for service bandwidths, service variety and number of service providers, asks for ever further penetration of fibre towards the end user residences. A number of key technologies are discussed for broadband service delivery through fibre access nework infrastructures, encompassing multiple access techniques exploiting the time, the frequency, and the wavelength domain. Particular attention is given to the currently most popular time division multiple access techniques in passive optical networks (APON, EPON, GPON), and to subcarrier multiplexing in hybrid fibre coaxial networks. Also some trends in access network research are highlighted, in partular dynamic network reconfiguration by means of optical routing, and fibre-wireless network techniques for meeting the booming needs of wireless services.

1 Introduction

Residential users have growing needs for all kinds of telecommunication services, such as traditional voice services, but also (increasingly personalized) video services, fast internet, fast peer-to-peer file exchange, high-quality audio, etc. The capacities needed per service vary widely: from 64 kbit/s for traditional voice telephony to beyond 100 Mbit/s for high-speed internet and data. The last link to connect to the end customer, the so-called first mile (or last mile, depending on the point of view), may be bridged with various types of transport media exploited by various network operators. Coaxial copper cable transports broadcast television and radio services, and increasingly also data services via cable modems. Twisted copper pair cables carry voice telephony, and data services via voice modems or high-speed ADSL and VDSL modems. Wireless systems bring mobile voice telephony via the GSM standard, and also data services via GPRS, UMTS, and Fixed Wireless Access (FWA). Optical fibre to the home/building is entering the market, but still has to surpass some cost barriers. It can offer the full set of integrated broadband services, from broadcast high bandwidth video services to

Medium	Bearer service	Bitrate (down/up)	Reach (km)
Twisted pair	analogue line	rates up to 56 k / 56 kbit/s	
Twisted pair	ISDN	144 k / 144 k data incl. 64 k / 64 k bit/s voice or data circuits	<6
Twisted pair	SDSL	768k / 768 kbit/s	<4
Twisted pair	ADSL	1.5 M to 6 M / 64 k to 640 kbit/s	<4 to 6
Twisted pair	VDSL	26 M to 52 M / 13 M to 26 Mbit/s	<0.3 to 1
Coaxial cable	CDMA/OFDM + QAM/QPSK	<14 M / 14 M (net 8.2 M) bit/s in 6 MHz slot	
Fibre (single mode)	ATM	150 M to 622 M / 150 M bit/s shared up to 1:32 (FSAN ATM-PON); up 1.24 G / 620 Mbit/s (FSAN/ITU B-PON)	<20
Fibre (single mode)	Gbit Ethernet	1 Gbit/s (1.25 Gbit/s 8 B/10 B coded)	<5
Fibre (multi mode)	Gbit Ethernet	1 Gbit/s (1.25 Gbit/s 8 B/10 B coded)	<0.55
Wireless (mobile)	GSM	13 kbit/s (at carrier freq. 900 and 1800 MHz, freq. duplex)	<16
Wireless (mobile)	GPRS	115 kbit/s	
Wireless (mobile)	UMTS	144 k to 2 Mbit/s (at carrier freq. 2110–2200 / 1885–2025 MHz, freq. duplex)	
Wireless (fixed)	MMDS	6 Mbit/s (at carrier freq. >17 GHz)	
Wireless (fixed)	LMDS	45 Mbit/s (at carrier freq. >17 GHz)	

Table 1 First-mile network technologies

Gigabit Ethernet data services. A list of first-mile media with the bearer services, bitrates and reach is given in Table 1. The need for more bandwidth in the access network is growing continuously, due to the increasing amount of bandwidth required by each customer, mainly fueled by video-based services and high-speed internet, the tailoring of services to individual customer needs, and the emergence of more competing operators due to liberalisation. This spurs the introduction of optical fibre (mainly single mode fibre, being a future-proof solution with its virtually infinite bandwidth) into the access network. As the network installation and equipment costs of fibre-to-the-home (FTTH) are still quite high in comparison to the traditional copper wired access lines, hybrid fibre access networks are the first step to introduce fibre. Fibre is used in the upper feeder part of the access network. There it runs from a local exchange (headend station) to a cabinet along the street (fibre-to-the-cabinet, FTTCab) or to the basement of a building (such as an apartment building with many living units; fibre-to-the-building, FTTB). At that point, the optical signals are converted back into electrical ones which are then brought via copper-based first mile links or wirelessly to the end customers.

In the next sections, after discussing some basic fibre-optic access network topologies and basic multiple access mechanisms, time- and frequency-slotted access techniques will be discussed in more depth which have been developed and are currently deployed for point-to-multipoint networks. Subsequently, some techniques which are still in the research labs for next-generation fibre access networks will be discussed: wavelength routing for dynamic capacity allocation, and radio over fibre for offering broadband wireless services. Finally, some concluding remarks are made and speculative prospects for the more distant future are given.

2 Fibre access network architectures

Basically, three architectures may be deployed for the fibre access network:

1 *Point-to-point* topology, where individual fibres run from the local exchange to each cabinet, home or building. Many fibres are needed, which entails high first installation costs, but also provides the ultimate capacity.

2 *Active star* topology, where a single fibre carries all traffic to an active node close to the end users, from where individual fibres run to each cabinet/home/building. Only a single feeder fibre is needed, and a number of short branching fibres to the end users, which reduces costs; but the active node needs powering and maintenance.

3 *Passive star* topology, 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 fibres to the end users. In addition to the reduced installation costs of a single fibre feeder link, the completely passive outside plant avoids the costs of powering and maintaining active equipment in the field. This topology has therefore become quite popular for introduction of optical fibre into access networks, and is widely known as the Passive Optical Network (PON).

In the point-to-point topology and the active star topology, each fibre link is carrying a data stream between two electro-optic converters only and the traffic streams of the users are multiplexed at these terminals, so there is no risk of collision of optical data streams. In the point-to-multipoint passive star PON topology, however, the traffic multiplexing is done optically by merging the data streams at the power combiner. Collision of the individual data streams needs to be avoided by well-designed multiple access techniques.

3 Multiple access techniques in PONs

The common fibre feeder part of the PON is shared by all the optical network units (ONUs) terminating the branching fibres. The traffic sent downstream from the optical line terminal (OLT) at the local exchange is simply broadcast by means of the optical power splitter to every ONU. Sending traffic from the ONUs upstream to the local exchange, however, requires accurate multiple access techniques in order to multiplex collision-free the traffic streams generated by the ONUs onto the common feeder fibre. Four major categories of multiple access techniques for fibre 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)

3.1 TDMA

In a *TDMA system*, as shown in Figure 1, the upstream packets from the ONUs are time-interleaved at the power splitting point, which requires careful synchronisation of the packet transmission instants at the ONUs. This synchronisation is achieved by means of grants sent from the local exchange, which instruct the ONU when to send a packet. At the local exchange in the OLT, a burst mode receiver is needed which can synchronise quickly to packets coming from different ONUs, and which can also handle the different amplitude levels of the packets due to differences in the path loss experienced.

TDMA techniques are deployed in ATM-PON, Ethernet PON and Gigabit PON architectures.

3.2 SCMA

In an *SCMA system*, illustrated in Figure 2, each ONU modulates its packet stream on a different electrical carrier frequency, which subsequently modulates the light intensity of the ONU's 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 may thus carry a signal in a format different from that in another channel (e.g. one channel may carry a high-speed digital data signal, and another one an analogue video signal). No time synchronisation among the channels is needed. The laser diodes at the ONUs 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 differently (e.g. by thermal tuning) in order to avoid this optical beat noise interference.

Subcarrier multiplexing techniques are being deployed in hybrid fibre-coax CATV networks.

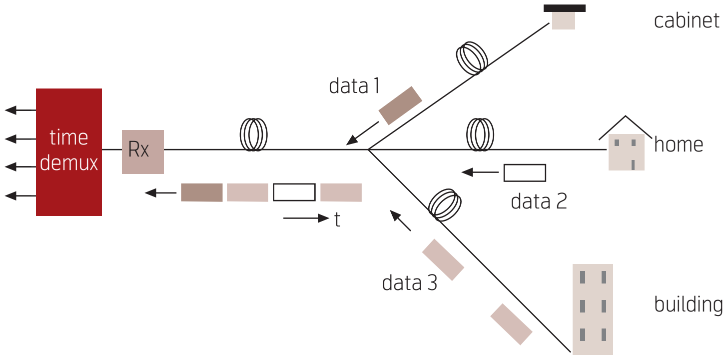


Figure 1 TDMA passive optical network

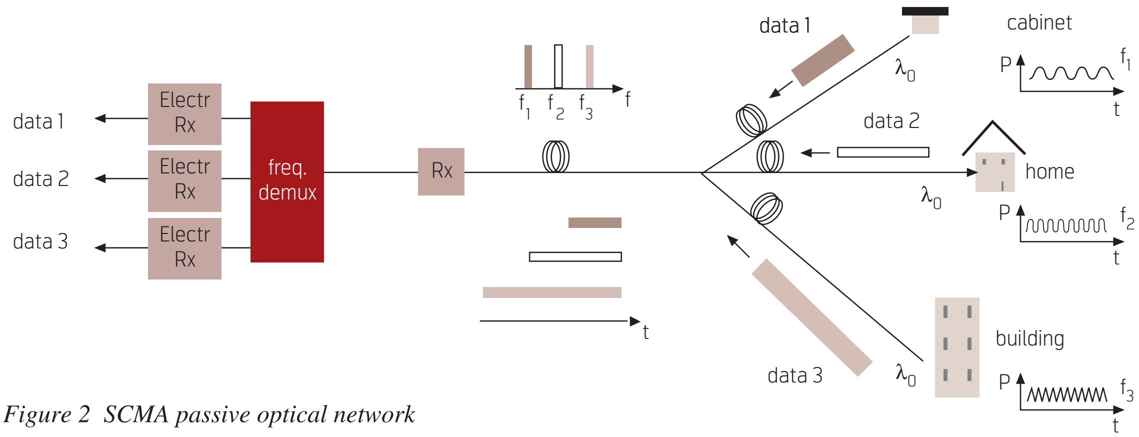


Figure 2 SCMA passive optical network

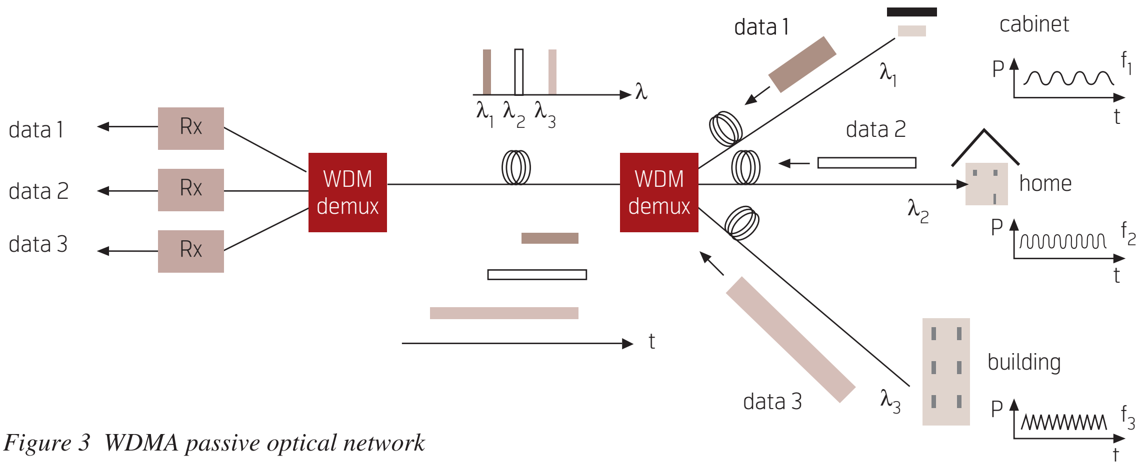


Figure 3 WDMA passive optical network

3.3 WDMA

In a *WDMA system* (see Figure 3), each ONU uses a different wavelength channel to send its packets to the OLT in the local exchange. These wavelength channels constitute independent communication channels and may thus carry different signal formats; also no time synchronisation is needed. The same wavelength channel may be used for upstream communication as for downstream. The isolation requirements of the wavelength demultiplexer should be high to sufficiently suppress crosstalk, e.g. when high-speed digital data and analogue video are carried on two different wavelength channels. The channel routing by the wavelength multiplexer at the network splitting point prohibits broadcasting of channels to all ONUs, as needed for instance for CATV signal distribution; a router bypass needs to be implemented for that. Every ONU needs a wavelength-specific laser diode, which increases costs and complicates maintenance and stock inventory issues. An alternative is to 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 reduces the inventory problems, but also yields a reduction of the effective optical power available from the ONU and increased intensity noise due to spectral instabilities of the source, and thus limits the reach of the system. Another alternative 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 [1]. Thus no light source is needed at the ONU, which eases maintenance; but again the power budget is limited.

3.4 OCDMA

In an *OCDMA system*, each ONU uses a different signature sequence of optical pulses, and this sequence is on-off modulated with the data to be transmitted. The duration of the sequence needs to be 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 ONUs. As the signature codes may not be perfectly orthogonal, some crosstalk may occur.

3.5 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 accommodated in electronic integrated circuits. Three types of TDMA passive optical networks have been addressed extensively in standardisation bodies: the ATM PON (APON) carrying native ATM cells following 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 and high efficiency (up to 2.4 Gbit/s up- and downstream) in the G.984 standard series.

Subcarrier multiplexing is particularly attractive for downstream broadband broadcasting, such as in hybrid fibre-coax CATV networks. In upstream direction, broadband communication in individual separate frequency bands requires a quite extended frequency range and high linearity of the user equipment, plus additional precautions need to be taken to avoid beat noise interference. Hence, SCMA is not commonly deployed in interactive fibre access networks.

WDMA offers the most powerful solution for multiple access, as it creates a virtual point-to-point topology. It is, however, also the most costly due to the additionally required wavelength selective functions. Some cost reductions may be achieved by using 'colourless' ONU techniques, such as a reflective modulator (e.g. reflective semiconductor amplifier) cooperating with a remote source, or spectral slicing of a broadband source. Using wavelength-based dynamic optical routing, very flexible future-proof access networks can be implemented, which can readily accommodate service upgrades, reallocation of traffic capacity, etc. Dynamic WDMA is an attractive solution for next-generation access networks, being addressed in research (see section 6).

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 fibre-optic access networks.

4 TDMA PON systems

4.1 ATM PON

The Full Service Access Network (FSAN) group, a committee of presently 21 major telecommunication operators around the world, has since 1995 been promoting the ATM PON (also termed APON or BPON) for broadband access networks.

4.1.1 ATM PON system architecture

As laid down in the G.983.1 Recommendation of ITU-T [2], 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 fibre 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 fibre (G.652) is foreseen. Coarse wavelength multiplexing is used for separating the bi-directional traffic: the downstream traffic is positioned in the 1.5 μm wavelength band, and the upstream traffic in the 1.3 μm band (using cheap Fabry Perot laser diodes in the ONUs).

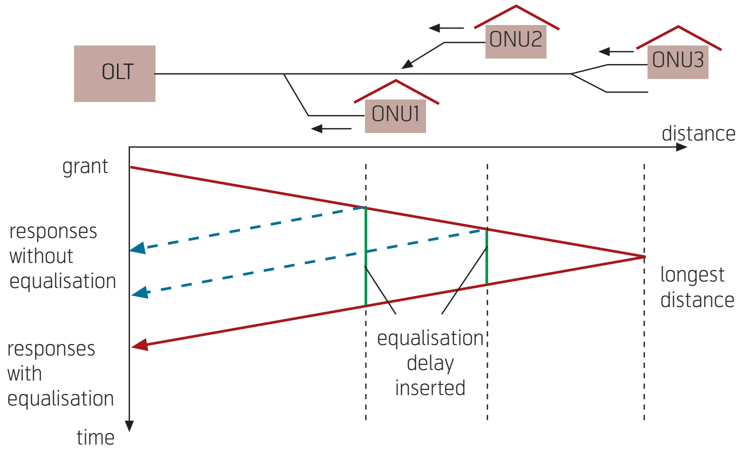


Figure 4 Time ranging in a TDMA PON

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 PLOAM cells (Physical Layer Operation, Administration, and Maintenance) of 53 bytes in a frame [2]. The PLOAM cells contain 53 upstream grants each. 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 broadcast to all ONUs. 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 fibre losses and the splitter losses are denoted by three classes of optical path losses: class A 5-20 dB, 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 [3]. The ONU receiver sensitivity at 155 Mbit/s should be better than -30 dBm for class B, and -33 dBm for class C.

The ONUs 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 [2] [5]. The OLT has to measure the distance to each ONU for this, and then instructs the ONU to insert an equalising transmission delay such that all distances from the ONUs to the OLT are virtually equal to the longest allowable distance (i.e. 20 km); see Figure 4. 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 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 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's 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.

4.1.2 Network protection

Four types of network protection have been described in Recommendation G.983.1 [5], as shown in Figure 5. Type A protection involves protection of the feeder fibre only by a spare fibre over which the traffic can be rerouted by means of optical switches. After detection of a failure in the primary fibre and switch-over to the spare fibre, also re-ranging has to be done by the PON transmission convergence (TC) layer. Thus only limited protection of the system is realised. Mechanical optical switches are used up till now; when optical switching becomes cheaper, this protection scheme may become more attractive. Type B protection features duplication of both the feeder fibre 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

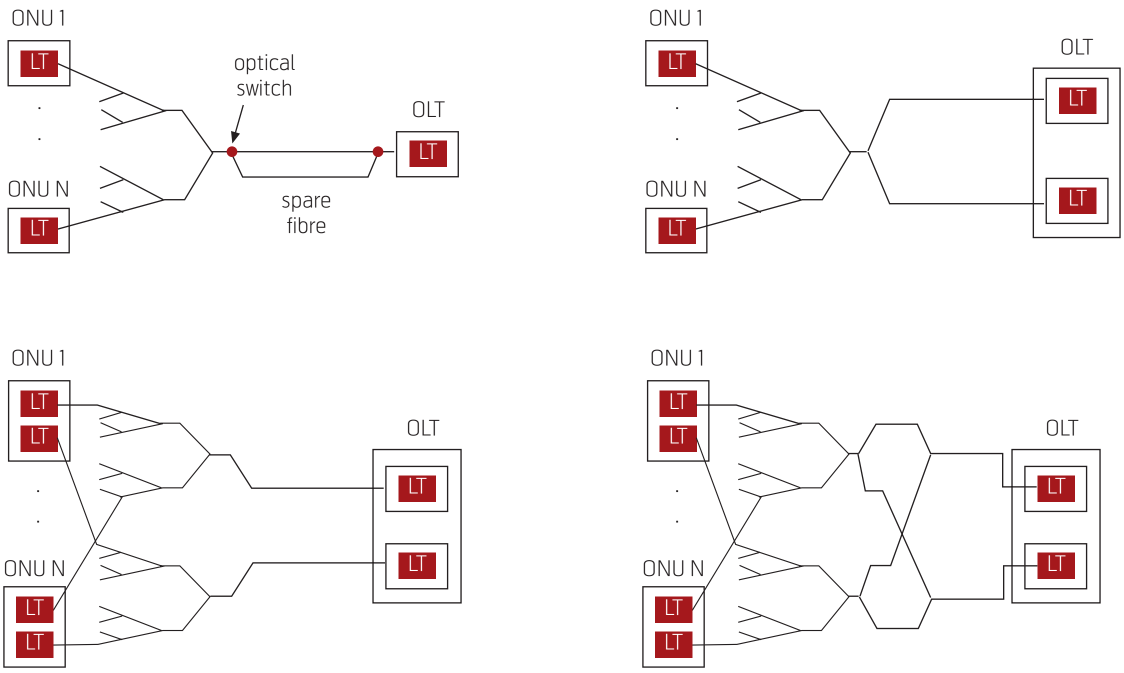


Figure 5 PON protection schemes
Type A: Feeder fibre protection; Type B: OLT and feeder fibre protection; Type C: Full PON duplication
Type D: Independent duplication of feeder and branch fibres

ONUs, 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 fibres as well as the ONUs are protected; also a mix of protected and unprotected ONUs can be handled. Type D protection features independent duplication of the feeder fibres and the branch fibres. 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 in G983.5.

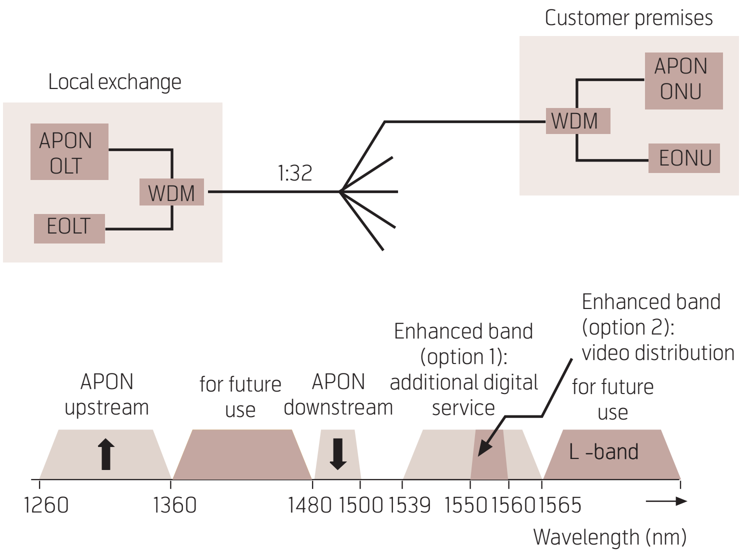


Figure 6 WDM enhancement G.983.3

4.1.3 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 622 Mbit/s burst-mode circuitry has been achieved recently [3]. In January 2003, ITU set standards for Gigabit-capable PONs (G-PONs). Further details are given in section 4.3.

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 [3], 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 Figure 6, the APON upstream services remain in the 1260 to 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 bi-directional 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 economical erbium-doped fibre amplifiers can thus 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 [4].

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 ONUs [5]. This extended split is achieved by creating a larger optical power budget. In the downstream direction, at the OLT a high power laser diode or an erbium-doped fibre 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 eight single-mode feeder fibres (each feeding a 1:16 or 1:32 power splitter in the field) are at the OLT coupled to a multimode fibre 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 realised in the SuperPON system [6]. An extension to a splitting factor of 1:2048 has been achieved; this however needs active equipment in the field. In the downstream direction exploiting the 1530–1560 nm wavelength window, EDFAs are used for overcoming the large path losses. In the upstream direction, gated semiconductor optical amplifiers (SOAs) 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 towards the OLT. This SuperPON approach is not compliant with present standards, and may be economically feasible only in the long term [5].

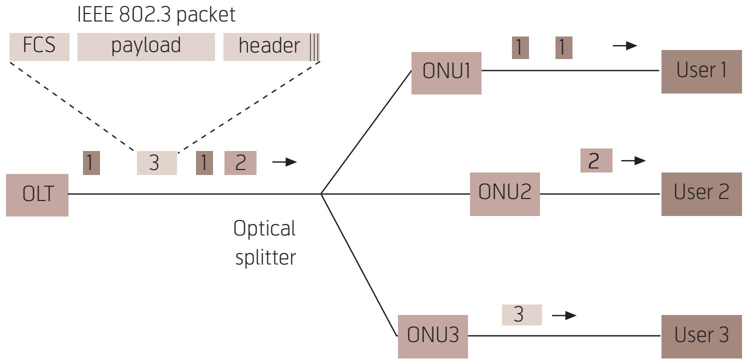


Figure 7 Downstream traffic in an EPON

4.2 Ethernet PON

With the rapid penetration of Ethernet-based services, Ethernet PON (EPON) techniques are receiving increasing attention and are promoted by the IEEE 802.3 Ethernet in the First Mile (EFM) group. The major difference from ATM PONs is that an EPON carries variable-length packets up to 1518 bytes in length, whereas an ATM PON carries fixed-length 53 bytes 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.

The EPON features full-duplex transmission similarly to the ATM PON, with downstream traffic between 1490 and 1510 nm and upstream traffic at around 1310 nm. As shown in Figure 7, standard IEEE 802.3 Ethernet packets are broadcast downstream by the OLT to all the ONUs. 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 2 ms duration, and each frame begins with a one-byte synchronisation marker. In the upstream direction, also 2 ms frames are used. A frame contains time slots that each are assigned to

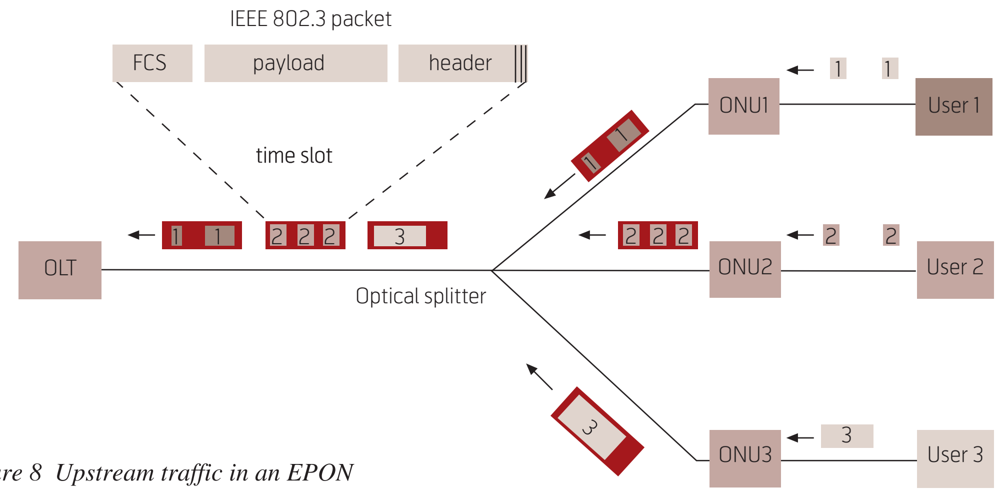


Figure 8 Upstream traffic in an EPON

one of the ONUs (see Figure 8). Each ONU puts one or more of its upstream variable-length IEEE 802.3 packets 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 is 125 or 250 μs.

4.3 Gigabit PON

In order to extend the capacity of PONs into the Gbit/s arena, the ITU has set standards for the Gigabit PON (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 fibre reach from OLT to ONU is 20 km whereas its minimum is 0. Protection schemes have also been foreseen, similar to those shown in Figure 5.

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 packetised traffic formats. This GPON Encapsulation Method (GEM) may host Ethernet packets, and/or native ATM packets, and/or native TDM, as illustrated in Figure 9 [7]. 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 out in G.984.4.

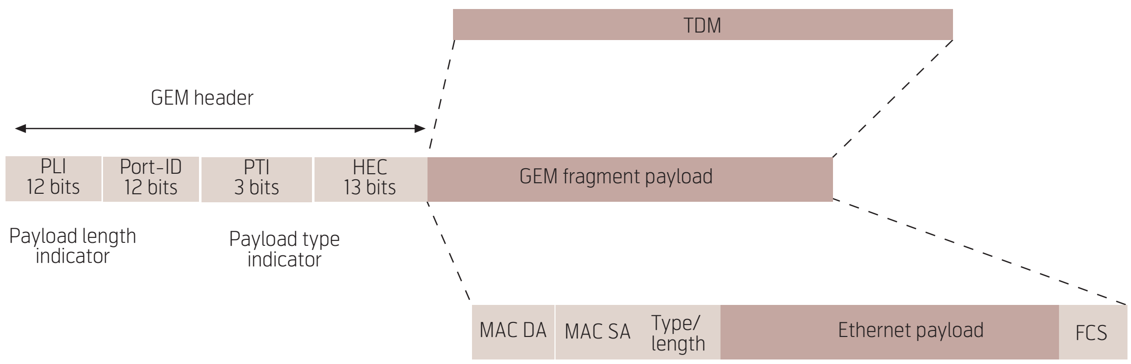


Figure 9 GPON encapsulation method according to ITU-T Rec. G.984.3

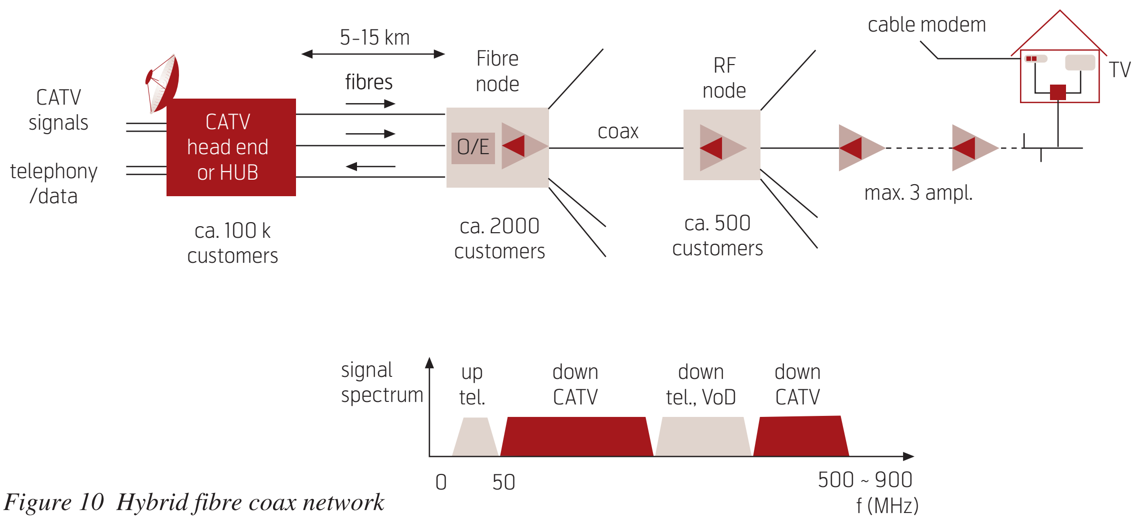


Figure 10 Hybrid fibre coax network

4.4 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 does not. EPON thus cannot support voice services with quality of service 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. On the other hand, ATM suffers from the cell tax (5 bytes header per 53 bytes 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 nicely combine the QoS advantages of ATM with the efficiency of Ethernet.

5 Hybrid fibre coax networks

CATV networks are usually laid out over large geographical areas and are mainly designed for downstream broadcasting of analogue TV channels (or digital TV channels, multiples of which fit into one analogue TV channel frequency slot) that are frequency-division multiplexed in a carrier frequency grid extending up to 1 GHz. As shown in Figure 10, in a hybrid fibre coax (HFC) system a CATV headend station collects the CATV signals, remodulates them into a specific frequency grid, and sends them via single-mode fibres to fibre nodes. Each fibre node converts the composite optical signal into an electrical one, which is carried via a coaxial cable network including several RF amplifiers to the residential homes. A single headend may thus serve hundreds of thousands of customers, and a fibre node some thousands of customers. In particular during transmission in the coaxial cable network, the signal quality deteriorates due to the addition of noise from the electrical amplifiers and intermodulation products from non-linearities in the system. On the fibre part of the network, the signals are carried with subcarrier multiplexing; see Figure 11. Each TV channel is amplitude-modulated on a separate frequency, and after summing all these modulated signals, a highly linear high power laser diode (or laser diode followed by a linearised external modulator) generates an optical signal which is intensity-modulated with the composite CATV signal. At the receiver site, the optical signal is converted into the electrical CATV signal by means of a highly linear PIN photodiode, and subsequently the signal can be passed to the coaxial cable network or to a selective receiver. When using a laser diode with low relative intensity noise and high linearity (or followed by a carefully linearised 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 fibre amplifiers can be used to boost the power at the headend and to compensate for the splitting losses; thus very extensive networks feeding thousands of ONUs can be realised. In this wavelength region, however, with direct laser modulation second order intermodulation products may arise due to laser chirp in combination with fibre chromatic dispersion; with an external modulator, however, the chirp is small enough to avoid these intermodulation products.

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

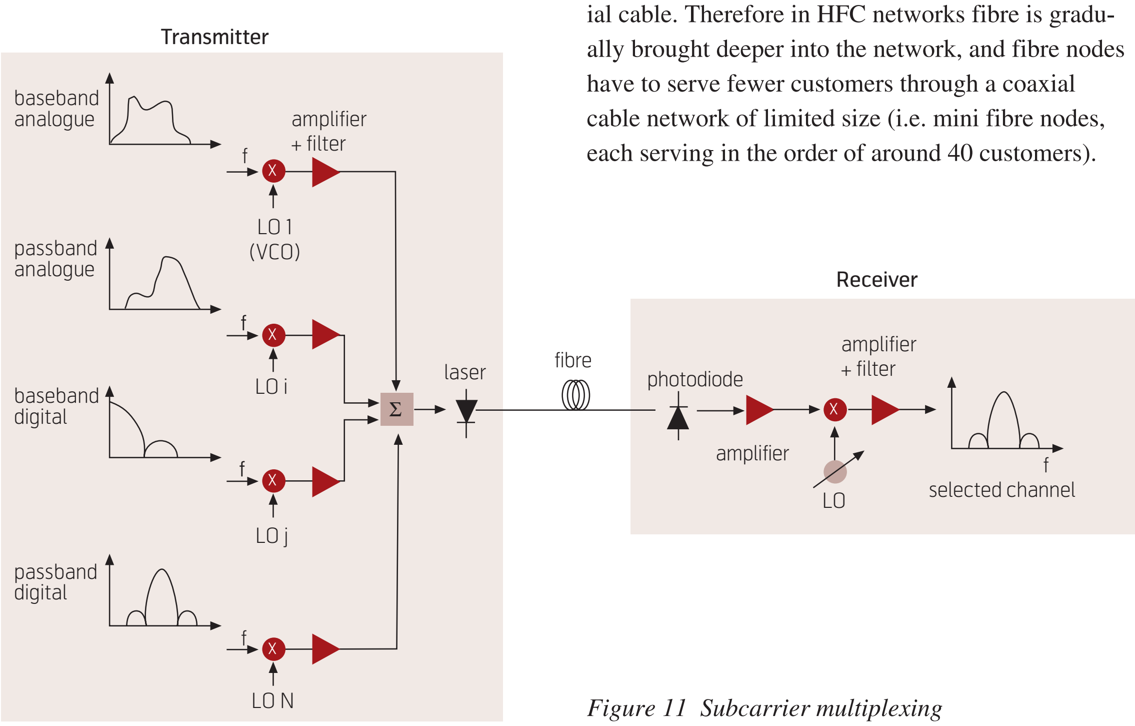


Figure 11 Subcarrier multiplexing

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 by using cable modems. For the upstream traffic which is involved with these interactive services and which is carried upstream in SCMA mode, parts of the spectrum unused for CATV and FM radio broadcast can be used. In Europe, typically the 5 to 65 MHz band is used for this; in the US, the 5–42 MHz range. For downstream data, e.g. the 300 to 450 MHz range is used, taking into account that Internet traffic is usually highly asymmetric (much more downloading traffic than uploading). Downstream per 8 MHz CATV channel, 30 to 50 Mbit/s data can be accommodated deploying 64 or even 256 Quadrature Amplitude Modulation (QAM). Upstream due to ingress noise less complicated modulation schemes are to be used; DQPSK offers about 3 Mbit/s per channel.

6 Dense wavelength multiplexing in access networks

In general, access networks have to meet a fast growth in capacity demand for several reasons. Customers are asking for second and more telephone lines; internet data traffic is booming with higher data rates, more users and longer sessions on-line (even always on); intense peer-to-peer file transfer traffic; multiplayer on-line gaming; an increasing amount of video-based services; fast growth in number of mobile phone users and session frequency; new operators entering asking to rent capacity on existing access networks; etc. This hunger for more capacity and the strive for convergence of services on a single network can most adequately be met by bringing fibre ever closer to the end users, from where only a short copper cable based (or wireless) link has to be bridged to reach the customer. Ultimately, when installation and equipment costs have come down sufficiently, the most powerful network is achieved when fibre is running all the way to the customer's home (fibre to the home, FTTH).

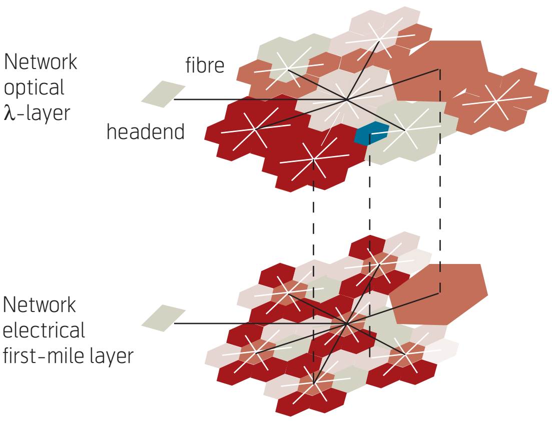


Figure 12 Dynamic wavelength routing in hybrid access networks

Upgrading installed fibre plant to higher capacities while protecting the investments already made can efficiently be done by introducing wavelength multiplexing techniques [8]. Wavelength channels may be allocated to specific sets of services (for service unbundling), and/or to separately host (new) service operators (leasing of network capacity).

6.1 Dynamic capacity allocation by flexible wavelength assignment

To cope with variation in service demand by the users and the sometimes quickly changing operator conditions, it is efficient to flexibly allocate the augmented available network capacity across the access network. Dynamic wavelength routing techniques can be used for this, thus making more efficient use of the network's resources and generating more revenues. Figure 12 illustrates the principle: from the OLT in the headend station of the network, multiple wavelength channels are fed to the ONUs via a tree-and-branch PON. By wavelength-selective routing in the PON, or wavelength selection at the ONU, wavelength channels can be assigned to a number of specific ONUs. Thus capacity can be specifically shared between these ONUs. Each ONU subsequently transfers its capacity share to its first-mile electrical network con-

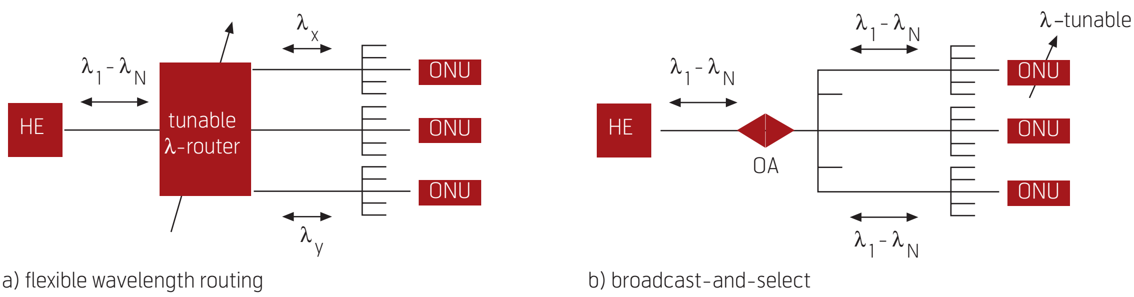
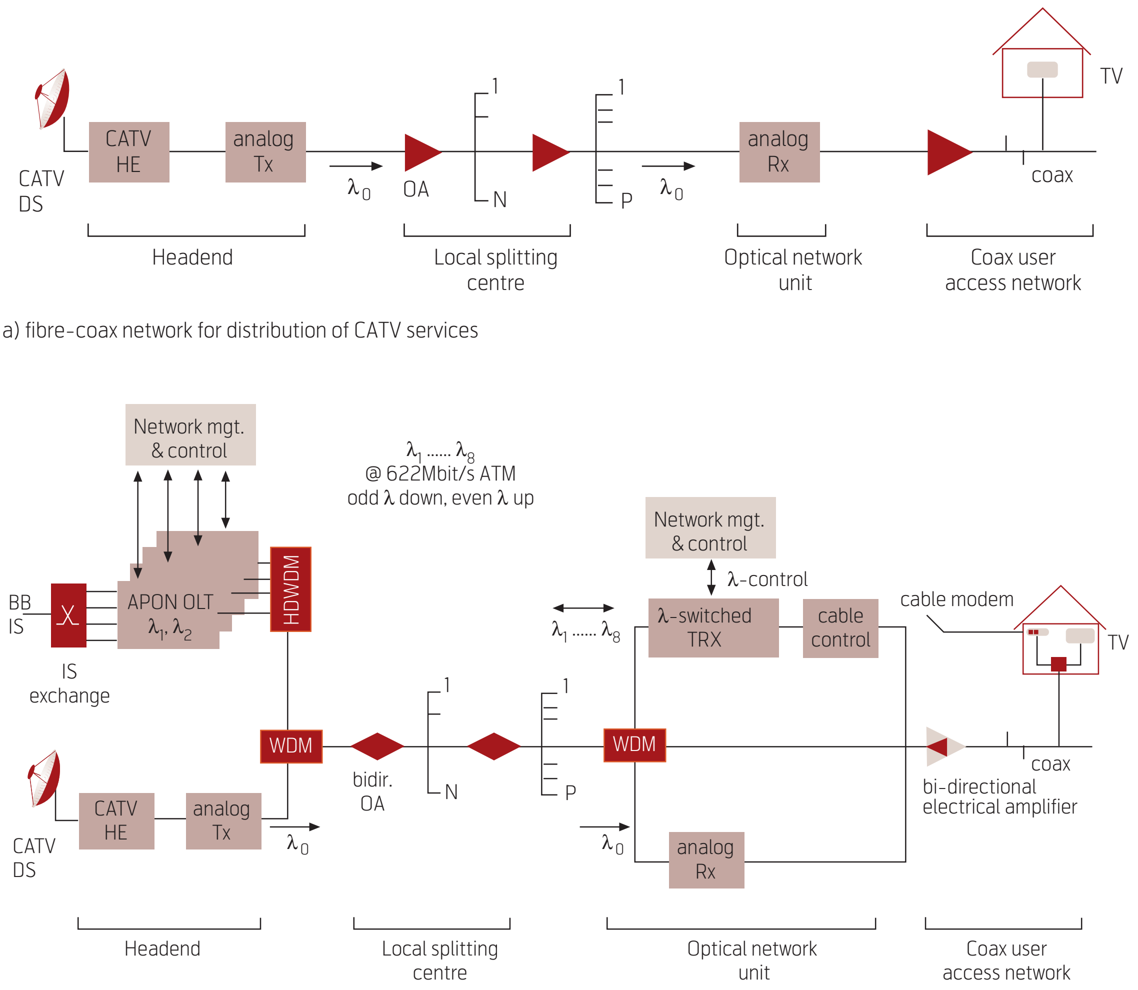


Figure 13 Dynamically allocating wavelength channels to ONUs

necting the end users. The mapping of the network capacity resources to the first-mile networks can thus be changed by changing the wavelength channel assignment among the ONUs. Basically two approaches can be followed for this, as illustrated in Figure 13: a wavelength router in the field, or wavelength selection at the ONUs. As shown in Figure 13.a, a tunable wavelength router directs the wavelength channels to specific output ports, and this routing can be dynamically adjusted by external control signals from the headend. In order to also support the delivery of broadcast services to all ONUs, 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 ONUs whose customers require the associated services, no optical power is wasted. As shown in Figure 13.b, another approach is to broadcast all wavelength channels to every ONU, and subsequently tune each ONU to the wavelength channel wanted. Clearly the power of the non-wanted wavelength channels is wasted by 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 bi-directionally to handle downstream as well as upstream traffic. This approach inherently supports broadcast services.

6.2 Wavelength broadcast-and-select access network

Figure 14 presents a multi-wavelength overlay of a number of ATM PON networks on a HFC network, following the *wavelength channel selection* approach [9]. Figure 14.a shows a fibre-coax network for distribution of CATV services, operating at a wavelength λ_0 in the 1550–1560 nm window where erbium-doped fibre amplifiers (EDFAs) offer their best output power performance. Thus, using several EDFAs in cascade, an extensive optical network splitting factor can be realised 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 mini-fibre node serving 40 users via its coaxial network, a total of 2560 users is served from a single headend fibre. For interactive services, the upstream frequency band in a standard HFC network



a) fibre-coax network for distribution of CATV services

b) upgrading of the fibre-coax network with multi-wavelength APON system for delivery of broadband interactive services

Figure 14 Flexible capacity assignment in a multi-wavelength fibre-coax network by wavelength selection at the ONUs (with a width of some 40 to 60 MHz) has to be shared among these users, thus allowing only limited bitrates per user for narrowband services such as voice telephony.

An upgrade of the system in order to provide broadband interactive services can be realised by overlaying the HFC network with a number of wavelength-multiplexed APON systems, such as have been developed in the ACTS TOBASCO project [9] and are shown in Figure 14.b. Four APON OLTs at the head-end site are providing each bi-directional 622 Mbit/s ATM signals on a specific downstream and upstream wavelength pair. 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 uni-directional optical erbium-doped fibre 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 behaviour (to suppress crosstalk in burst-mode). At the ONU site, the CATV signal is first separated from the APON signals by means of a coarse wavelength multiplexer and 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 in principle can 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 upstream wavelength channel each ONU transceiver is switched. By issuing these commands from the headend station, the network operator actually controls the virtual topology of the network, and is thus 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 by the transceiver into a bidirectional electrical broadband data signal, which is by a cable modem controller put in an 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 to 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 bi-directional data signals. The latter signals are processed by a cable modem that interacts with the cable modem controller at the ONU site.

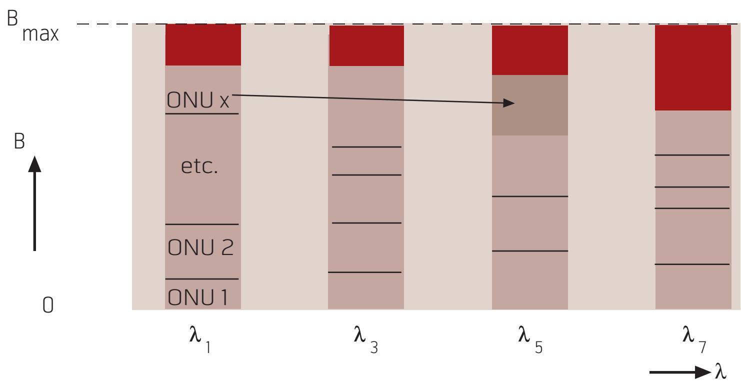


Figure 15 Re-allocating ONUs to wavelength channels

By remotely changing the wavelength selection at the ONUs, 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 Figure 15, the ONUs are allocated to the four upstream (and downstream) wavelength channels, each having a 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 another wavelength channel, in which sufficient free capacity is still available. Obviously, this dynamic wavelength re-allocation process reduces the system's blocking probability, i.e. it allows the system to handle more traffic without blocking and thus can increase the revenues of the operator.

6.3 Wavelength routing access network

Figure 16 presents the *dynamic wavelength channel routing* approach in a fibre-wireless network to allo-

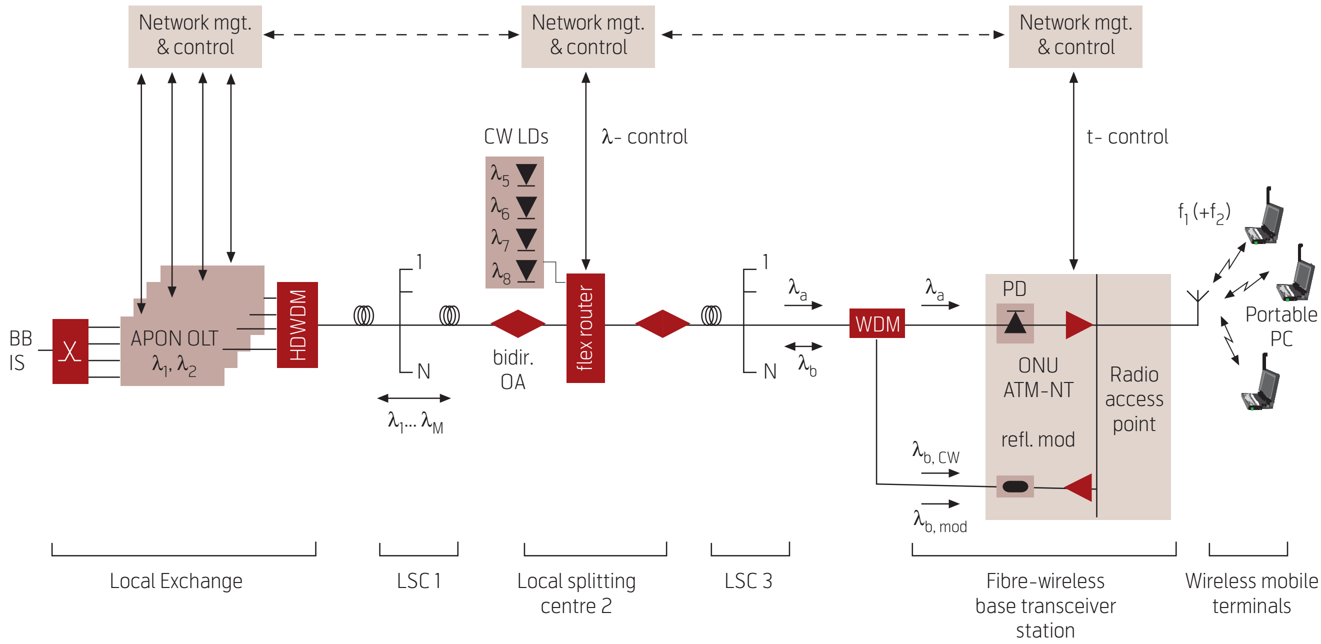


Figure 16 Flexible capacity assignment in a multi-wavelength fibre-wireless network by wavelength routing in the field

cate flexibly the capacity of a number of ATM PON systems among ONUs in a single fibre split network infrastructure [10]. Each ONU feeds a radio access point (RAP) of e.g. a wireless LAN, which wirelessly 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), 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 re-allocation of the wavelength channels over the ONUs, which is done by a flexible wavelength router positioned in the field. Similar to the architecture of the wavelength-reconfigurable fibre-coax network in Figure 14.b, the architecture in Figure 16 (which was developed in the ACTS PRISMA project) has four 622 Mbit/s bi-directional APON OLTs 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 each downstream wavelength channel to one or more of its output ports, and thus via a split network to a subset of ONUs. The RAPs could operate with up to 5 microwave carriers in the 5 GHz region, each carrying up to 20 Mbit/s ATM wireless LAN data in OFDM format. At the flexible router (or at the local exchange) a number of continuous-wave emitting laser diodes are located, providing unmodulated light power at the upstream wavelengths. The flexible router can select one of these upstream wavelengths and direct it to the ONUs 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 ONUs, and all ONUs 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 as depicted in Figure 15 to assign wavelength channels to the ONUs, 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 according to a Poisson process where the call duration and length were uni-

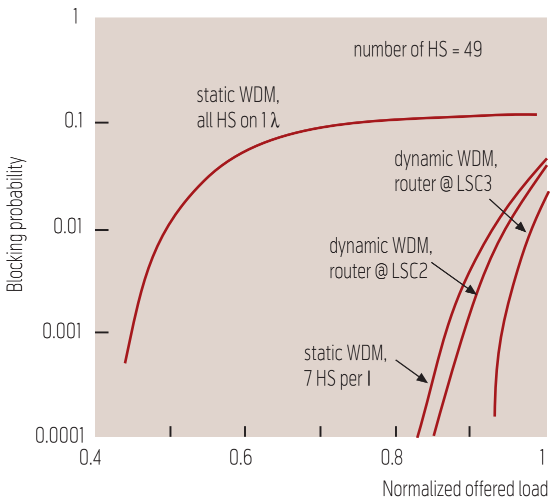


Figure 17 Improving the system performance by dynamic wavelength allocation

formly distributed. Figure 17 shows how the system blocking probability depends on the offered load (normalised on the total available capacity, which is 7 times 622 Mbit/s), using various system architecture options. When wavelength re-allocation would not be possible (i.e. static WDM) and all the 49 hot spots were positioned at cells served by ONUs assigned to the same wavelength channel, the blocking probability is obviously the worst. On the other hand, in the static WDM case when 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 this static WDM situation 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 dynamic re-allocation of the wavelength channels is possible, however, the system can adapt to the actual hot spot distribution. Figure 17 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 optimising 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 ONUs. Locating the router at the second splitting point is a good compromise between adequate improvement of the system blocking performance and system costs per ONU.

7 Microwave signals over fibre

Wireless communication services are steadily increasing their share of the telecommunication market. Next to their prime feature, mobility, they need to offer growing bandwidths to the end users. This entails also an increase of the radio carrier frequencies, which leads to smaller radio cell coverage (due to the 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, evolving 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, Fixed Wireless Access up to 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 Radio Access Points (RAPs) are needed to serve e.g. all these rooms in an office building, and hence also a more extensive wired network to feed the 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 considerably. The signal processing functions can thus be consolidated at the headend site. Thanks to its superb broadband characteristics, optical fibre is an excellent medium to bring the microwave signals to the RAPs.

7.1 Heterodyning systems

Carrying multi-GHz analogue signals over fibre requires very high frequency optical analogue transmitters and receivers, including careful fibre dispersion compensation techniques. An attractive alternative avoiding the transport of multi-GHz intensity-modulated signals through the fibre 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 realised, while the complicated signal processing is consolidated at the headend station.

This approach, however, requires two light sources with narrow spectral linewidth and carefully stabilised difference between the optical emission frequencies. An alternative approach requiring only a single optical source is shown in Figure 18 [11]. The optical intensity-modulated signal from a laser diode is subsequently intensity-modulated by an external Mach Zehnder modulator (MZM) which is biased at the inflexion point of its modulation characteristic and driven by a sinusoidal signal at half the microwave frequency. 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 multi-wavelength radio-over-fibre system can be realised with a (tunable) WDM filter to select the desired wavelength radio channel at the antenna site. The system is tolerant to fibre dispersion, and also the laser linewidth is not critical as laser phase noise is largely eliminated in the two-tone detection process.

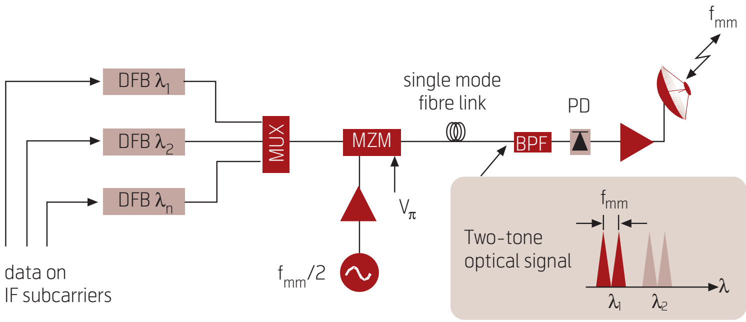


Figure 18 Generating microwave signals by heterodyning

7.2 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, is shown in Figure 19 [12]. 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. The intensity of the wavelength-swept signal is on/off modulated with low frequency chirp by the downstream data in a symmetrically driven Mach Zehnder modulator. After travelling through the fibre network, at the receiver the signal transverses 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 transversing an electrical bandpass filter (BPF) which rejects the unwanted harmonics. Theoretical analysis and simulations have shown that the microwave signal is very pure; the inherent cancellation of the laser's optical phase noise causes the spectral linewidth of the microwave signal to be much smaller than that of the laser diode. Experiments have shown e.g. the generation of a microwave linewidth less than 50 Hz,

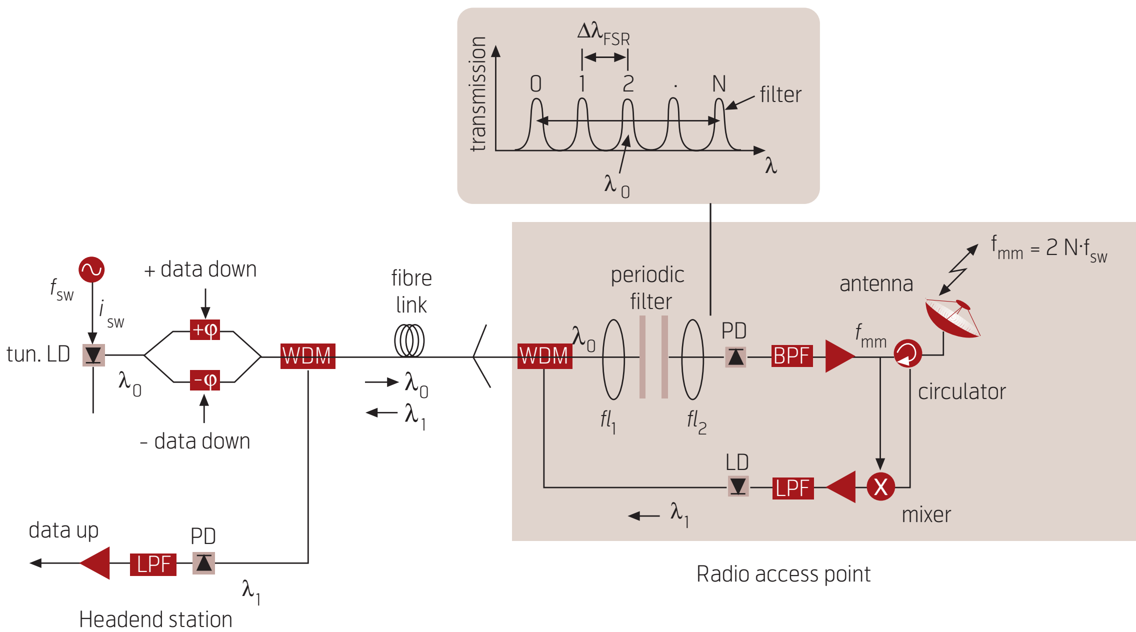


Figure 19 Generating microwave signals by optical frequency multiplying

whereas the laser linewidth exceeded 1 MHz [13]. The periodic optical bandpass filter can be advantageously implemented by a Fabry Perot 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, due to its spectral purity; e.g. 16-level Quadrature Amplitude Modulated (16-QAM) signals may be modulated on a subcarrier first, and then drive the Mach Zehnder Modulator. 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 1 GHz), which can easily 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, and thus may also operate on multimode fibre networks (such as polymer optical fibre, which is easy to install inside buildings).

Assuming a linear behaviour of the fibre, it can be shown that the periodic optical filter may also be positioned at the headend site, 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 [14].

The system can also transport upstream data from the antenna station to the headend. 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 down-shifted, and be used for down-converting the upstream microwave signal from the mobile terminal to a tunable intermediate frequency. This downconverted signal can subsequently be transmitted upstream on a separate wavelength by an IF-frequency optical transmitter [14]. Tuning to a different IF per antenna station enables the use of an SCMA upstream transmission protocol.

8 Concluding remarks

Optical fibre is now generally recognised to be the most powerful medium for transporting information, due to its very low losses and extremely wide bandwidth. Next to space and time multiplexing, the wavelength dimension offers unprecedented opportunities to extend not only the data traffic transport capacity, but also the traffic routing possibilities in networks.

In access networks, fibre is penetrating steadily towards the end user. Infrastructure costs are the major nut to crack here. Shared-feeder concepts such as the passive optical network tree-and-branch one greatly reduce the installation costs of the fibre network, and can support various multiple access techniques (ATM and Ethernet for time multiplexed access, among others). 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, fibre can support a wide range of last-mile technologies by hybrid combinations such as fibre-twisted pair, fibre-coax, and fibre-wireless. By means of wavelength multiplexing techniques, the fibre feeder part of such hybrid networks can very flexibly host different operators and service categories. Augmented with wavelength routing, capacity-on-demand can be realised for e.g. handling hot spots, while respecting Quality of Service requirements. By deploying advanced techniques for transporting microwaves over fibre, 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.

9 Future prospects

With the ongoing improvements in fibre characteristics and development of novel optical amplifier structures, the wavelength range available for communication will stretch from below 0.8 μm to beyond 1.6 μm, covering a bandwidth of some 200 THz. Further improvements in signal coding yielding a higher spectral efficiency, in ultra-dense wavelength division multiplexing and in ultra-high speed optical time division multiplexing will enable us to exploit this huge bandwidth, and will push the transport capacity of a single fibre beyond 100 Tbit/s.

The end user is to benefit from all these ultra-broadband communication possibilities. Therefore the optical fibre will not only reach up to his house, but it will penetrate into it as well. It will reach close to his personal area network, which thanks to the ongoing miniatuarisation may consist of a myriad of small wireless power-lean terminals, sensors and actuators. These wireless devices will 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, these wireless devices will be connected to the fixed in-home and access network by a myriad of small intelligent antennas. Radio-over-fibre techniques, augmented with optical routing to accommodate dynamically the hot spots, will provide the best match of the ultimate capacity of fibre 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 will 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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Ton Koonen is since 2001 a full professor at the COBRA Institute at Eindhoven University of Technology in the Netherlands. Prior to that, he spent more than 20 years at Bell Labs in Lucent Technologies as a technical manager of applied research. He also is a Bell Labs Fellow. Next to his industrial position, he was a part-time professor at Twente University from 1991 to 2000. His main interests are currently in broadband fibre access networks and optical packet-switched networks. He has initiated and led a number of European and national R&D projects in this area, among others in dynamically reconfigurable hybrid fibre access networks for fibre-to-the-curb and fibre-to-the-building. Presently, he is involved in several projects in the European FP6 IST programme on access networks.

email: A.M.J.Koonen@tue.nl