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Optical Heterodyne Systems

Coherent Multicarrier Lightwave Technology for Flexible Capacity Networks

Highly flexible and survivable networks can be built by allocating optical carriers of heterodyne systems.

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Important advantages offered by optical heterodyne systems are the selectivity and tunability of the receivers. Heterodyne receivers can be seen as an almost ideal optical filter with very attractive features. The optical filtering function, which corresponds to the narrow passband of the receiver, can be tuned rapidly to any desired optical carrier within a wide frequency range [1]. A tuning range of more than 7 nm and a passband of around 1 GHz can be realized simultaneously.

The optical transmitter carrier frequency of heterodyne systems can be varied as well. Heterodyne systems thus appear to be a very attractive technology for the realization of networks in which optical multicarriers can be allocated in a flexible way. Such networks can serve as survivable routes with a flexible capacity in the core network and in multiple-access systems for business users. Another advantage is that the attractive features just described are not restricted to the passband of a certain optical amplifier. Heterodyne systems can be used over the entire wavelength range offered by the single-mode optical fiber, from 1250 to 1600 nm.

Another technical advantage offered by heterodyne detection is the superior receiver sensitivities and related transmission spans. That advantage has been partly eroded since the introduction of optical fiber amplifiers. An optical receiver operating without the heterodyne method but equipped with an optical fiber preamplifier and some other special measures [2] has a sensitivity similar to that achieved with a heterodyne receiver.

Recent work in Europe concentrates on the exploitation of the earlier described flexibility features. The work is being pursued within the framework of the European Community program, Research and Technology Development in Advanced Communications Technologies in Europe (RACE), and directed toward the implementation of multicarrier systems in field trials.

The basic features of heterodyne systems will be reviewed, especially in view of the use of multicarriers, tunability, and selectivity. Then specific application areas that may benefit from flexible multicarrier allocation schemes will be discussed. Examples will be taken from the RACE Phase II project R2065, coherent optical systems implemented for business traffic routing and access (COBRA). Next, trends and progress in heterodyne systems in general and related key components will be summarized, and then examples of ongoing field trials in Europe will be discussed. Finally, the coherent multicarrier technology will be compared briefly with direct detection multiwavelength technology.

Basic Principles and Capabilities

The principle of optical heterodyne detection is shown in Fig. 1a. An incoming optical signal is converted into a radio frequency signal of intermediate frequency (IF). A local oscillator (LO) laser, together with an optical coupler and a photodiode, is used for the conversion process. The IF signal is detected using methods derived from conventional radio techniques. In principle, optical systems based on heterodyne detection use techniques and principles similar to those developed for radio systems. System details depend on modulation formats such as amplitude shift keying (ASK), frequency shift kkeying (FSK), and differential phase shift keying (DPSK). Bit rates ranging from 155 Mb/s to 2.5 Gb/s have been used in field trials.

Figure 1b [3] illustrates how two optical frequencies f_S and f_{LO} of equal amplitudes are converted into a frequency IF, which is the envelope of the "mixed" frequency f_M. The frequency values given as an example in Fig. 1a indicate why the optical heterodyne receiver acts as an almost perfect optical filter. Using well-known electrical filtering techniques, it is easy to realize, for example, a bandpass of a few hundred megahertz around the IF frequency of 1 GHz. A pure optical domain filter

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with comparable properties would mean that a passband of a few hundred megahertz would have to be made around an optical signal carrier of about 200 THz. Today, LO lasers can be tuned over a range of 7 nm, and the heterodyne receiver thus acts as an optical filter that combines high selectivity with wide tunability.

Using heterodyne techniques, it is possible to exploit the enormous bandwidth potential of the optical fiber in an efficient way. Single-mode fibers used today can be used in the wavelength region ranging from about 1250 to 1600 nm. That range represents a bandwidth of around 50,000 GHz. If the signal carrier frequencies of the heterodyne systems are separated by 10 GHz from each other, 5000 carriers can be accommodated simultaneously in that wavelength region.

The minimum optical channel spacing between carriers of a heterodyne system is dependent on the value of IF and the minimum electrical domain channel spacing. A multicarrier system for N x 155 Mb/s will require less channel spacing than a system accommodating N x 2.5 Gb/s.

Connection Examples

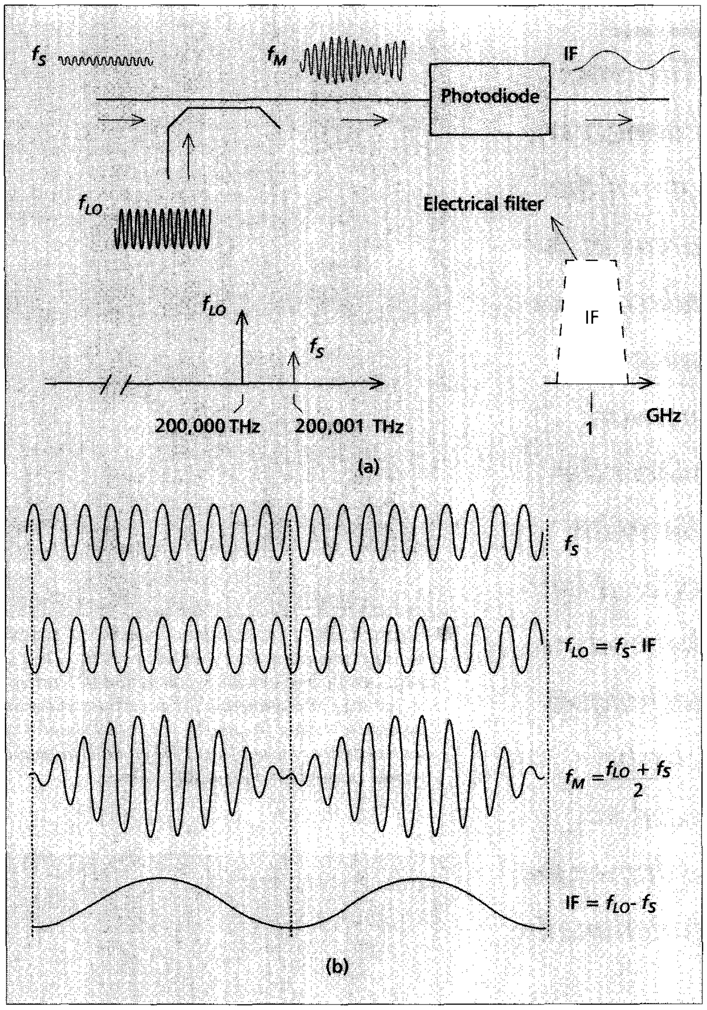
Tunable transmitter lasers and LO lasers are available today, and any pair of signal and LO frequencies can be formed within the tuning range of those lasers to create a desired IF signal. Possible combinations are illustrated in Fig. 2. For a simple link, it is common to use a transmitter laser and a LO laser with fixed frequencies. In a distribution system, each heterodyne receiver can be tuned to any of the incoming signals. In a multi-access system, each of the transmitters and receivers can be tuned to each other to establish a communication channel. By properly allocating the pairs of signal and LO frequencies, the channels will not disturb each other, owing to the perfect filtering properties of the receivers. It has been demonstrated recently that a tunable diode laser can be used to switch and lock a receiver to an incoming signal within 0.5 μs [4]. Such speeds will open the way towards applications in the area of data packet switching as well.

Full duplex or even full multiplex connections can be established without the need to duplicate transmitters and receivers. Part of the optical signal of the LO can be modulated and sent back into the same fiber link, as shown in Fig. 3. The heterodyne receiver can thus operate as a single laser transceiver (transmitter-receiver) [5-7]. Connections between heterodyne transceivers can therefore offer full duplex or even full multiplex channels [6].

Incorporation of heterodyne techniques is therefore attractive in those system areas where high capacity, high flexibility, and multi-access capabilities are required. We point out in the next section that the heterodyne technique does not conflict with other techniques. On the contrary, it is a very attractive method to complement time domain and other optical domain methods.

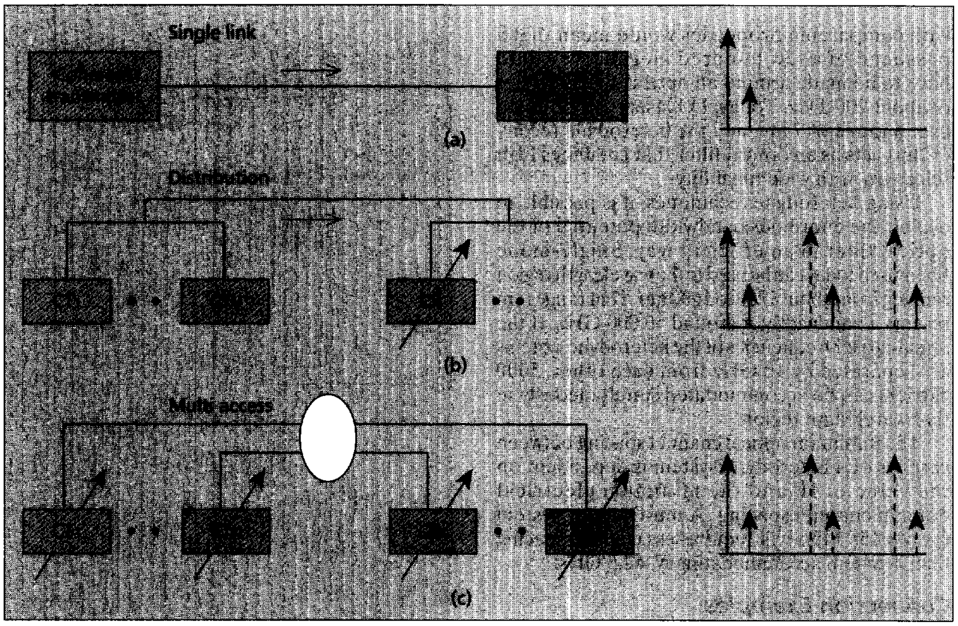
Combination with Other Technologies

The evolution in telecommunication networks is strongly influenced by the synchronous digital hierarchy (SDH), a standard [8, 9] that deals with aspects of time multiplexing of present and future communication channels and that assumes the use of an optical network for the high bit rates on the lines. The role of optics in the present SDH-based network is restricted only to transmission, while the flexibility provided by switching and multiplexing functions is performed by electrical means. SDH supports flexible transportation capabilities offered by ATM techniques [9, 10]. A hierarchical principle was introduced within the ATM networks to simplify the management of signal flow and transfer. The layers within such a hierarchy are called ATM "channels" and ATM "paths," as indicated in Fig. 4 [9, 11, 12]. The ATM path can be considered as a "pipe" supporting a cluster of ATM channels.

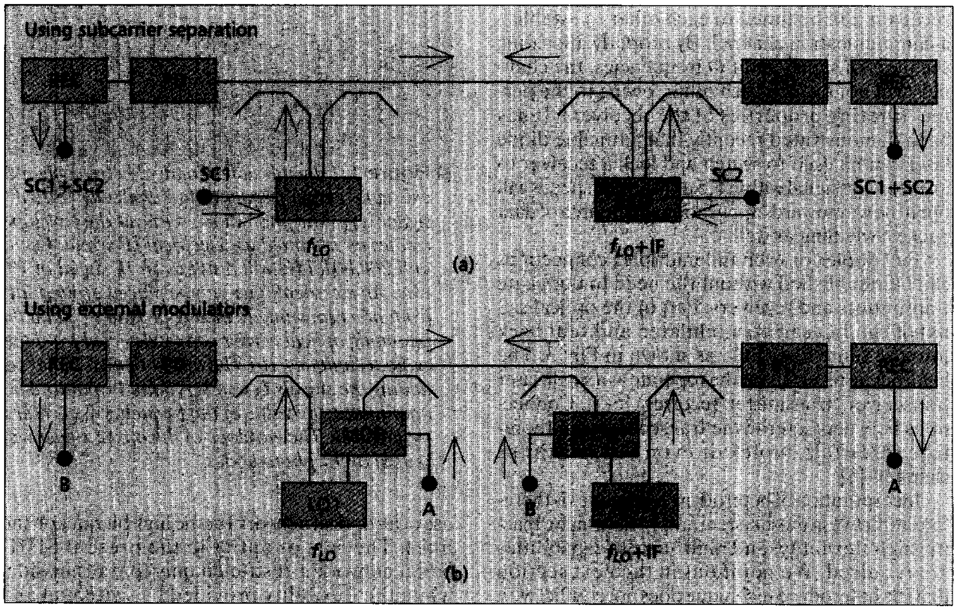


■ Figure 1. *Principles of an optical heterodyne receiver. (a) An incoming optical signal with a frequency* f_S *is optically "mixed" with a signal from an LO, signal* f_{LO}*. The photodiode retrieves the envelope of the mixed signal* f_M *and creates an intermediate electrical IF signal. Optical frequencies of 200 THz and 200,001 THz will result in an IF signal of 1 GHz when processed in this way. An electrical filter can be placed around the IF of 1 GHz to separate it from other unwanted "mixing products." Data that was modulated on the incoming optical carrier can be detected from the IF using "conventional" radio techniques. (b) The mixed optical signal can be constructed by simply adding the signals* f_S *and* f_{LO} *point by point. When* f_S *and* f_{LO} *have equal amplitudes, the value of the frequency* f_M *is half of the sum of the two mixed frequencies. The envelope of the mixed signal will show up at the electrical output of the photodiode.*

The cross-connect is one of the areas in the telecommunication network where the flexibility offered by heterodyne techniques can be used to enhance the functionality.



■ **Figure 2.** *Basic capabilities of heterodyne systems. (a) Point-to-point connections can be served by implementing one transmitter and one receiver. The capacity of such point-to-point connections can be increased by implementing coherent multicarrier (CMC) systems where a number of parallel optical carriers are used simultaneously. Paired transmitters and receivers are operated simultaneously, each at a different optical carrier frequency. (b) A distribution system can be realized by means of a CMC system when the receivers are tunable. (c) When both transmitters and receivers are tunable, a multi-access system is created around an optical star coupler.*

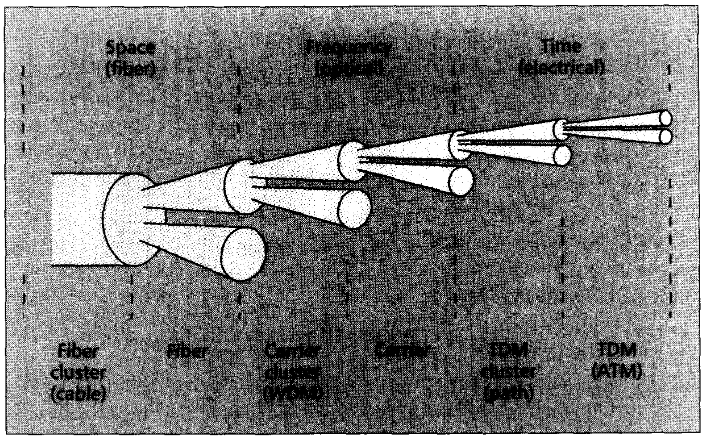


■ **Figure 3.** *Heterodyne receivers that can be operated as transmitters at the same time, using just one laser. This single-laser transceiver can be used to establish full duplex connections: (a) The LO laser is modulated with data which is carried by a microwave carrier subcarrier (SC) [72-74]. Part of the optical signal of the modulated LO is coupled back into the fiber link. If both sides of the fiber link are connected to a transceiver, collision of the data will occur in the electrical domain. However, if the values of SC1 and SC2 are different and chosen properly, the detection part of the electrical receiver can separate the microwave carriers from each other easily. More than two transceivers can communicate with each other in a full multiplex mode if more than two different subcarriers are used. (b) Part of the unmodulated optical signal of the LO laser is coupled into an optical modulator and subsequently coupled back into the fiber link. This option can only offer a full duplex connection.*

Following the same concept, we propose to introduce further multiplex hierarchies using the optical domain techniques [12, 13], as shown in Fig. 4. Each optical carrier can be used to transport, using heterodyne technology, a cluster of ATM paths at a standard bit rate of, for example, 2.5 Gb/s. Clusters of optical carriers can be grouped into a wavelength-division multiplex (WDM) layer. The WDM option separates the optical domain into wavelength bands with a width of a few nanometers each, using optical domain filter techniques [14, 15]. Each of these wavelength bands can accommodate many narrowly spaced optical carriers, supporting a multicarrier heterodyne system.

The optical fiber and cable can be considered as further hierarchies in the telecommunications network. Although optical fibers will not be physically moved around to provide flexible connections, the functionality as such may be realized by introducing optical space switches.

It is clear that optical domain techniques can complement the existing (electrical) time domain methods in a very attractive way. Using heterodyne techniques, WDM, and optical space switching, telecommunications networks can gradually evolve towards broadband networks with huge capacity and high flexibility.



■ **Figure 4.** *Hierarchical representation of multiplexing technologies in the telecommunication networks. The lowest level is represented by TDM techniques. ATM is considered to be an important method. In the ATM hierarchy, ATM channels are clustered into ATM paths. The optical carriers of heterodyne systems can be seen as a next layer which can support a cluster of ATM paths up to a standard bit rate of, for example, 2.5 Gb/s. A cluster of these narrowly spaced heterodyne carriers can be grouped into a next layer, separated from each other by WDM techniques. According to the WDM option, the optical domain is divided into bands of a few nanometers each by means of optical domain filtering techniques. The fiber and cable can be seen as further levels in the proposed hierarchy. Fibers and cables can accommodate flexibility functions if provided with optical space switches at the proper locations.*

Illustration of the Flexibility Aspect

The crossconnect is one of the areas in the telecommunications network where the flexibility offered by heterodyne techniques can be used to enhance the functionality. Optical systems operating without heterodyne receivers, called "direct detection" systems, are commercially available today. Those direct detection systems operate at the SDH level of 2.5 Gb/s. We will therefore use a crossconnect with 2.5-Gb/s fiber outputs and inputs as a basis for our example. Within the crossconnect itself, the 2.5-Gb/s signals will be broken down into smaller units with lower bit rates to allow routing of the different information flows. Advanced crossconnects will commonly serve as a node with optical fiber connections operated at a fixed transmission bit rate of 2.5 Gb/s each. One possibility for increased throughput of the node is to incorporate a bit rate of 10 Gb/s, the next SDH level, in each fiber link. Another possibility is to introduce a heterodyne multicarrier system, operating at 2.5 Gb/s/carrier, as an overlay to the existing electrical 2.5-Gb/s SDH node. A node with the heterodyne multicarrier overlay will be called a reconfigurable node (RENO).

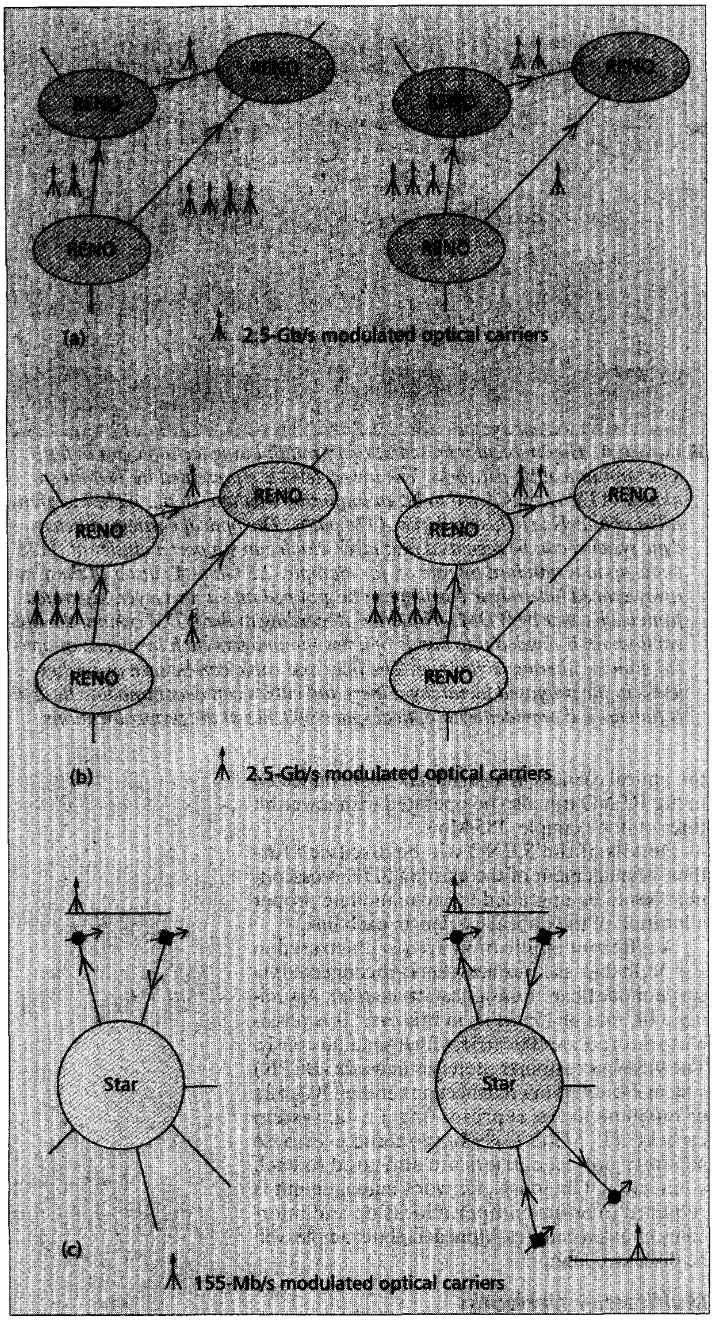
The RENO can offer a throughput of N x 2.5 Gb/s per fiber. Figures 5a and 5b illustrate the reconfigurability of such a node. In Fig. 5a, the capacity of fiber links interconnecting the RENOs are varied as needed by traffic requirement in a particular period of time. Special events may cause a temporary need to increase the capacity of a link between two nodes. In another time slot, the increase in capacity may be required between two other nodes. Failure in one of the links connecting two nodes is another reason for reconfiguring the connections, as shown in Fig. 5b. Using present-state heterodyne equipment, more than 16 carriers of 2.5 Gb/s each can be used simultaneously. The throughput of each link can therefore be varied from 2.5 to 40 Gb/s as necessary. Obviously, the optical carriers in a particular fiber connected to the RENO can also be operated with lower bit rates of, for example, 155 Mb/s.

Details of the RENO will be discussed further. Management of the existing SDH crossconnect has to be upgraded to accommodate proper allocation of the optical carriers in each link.

A different application area is illustrated in Fig. 5c. In this case, business users are connected via single-mode fibers to an optical star coupler. Assuming a bit rate of 155 Mb/s in this case, it is possible to incorporate 100 carriers/fiber simultaneously. The business customer premises network (BCPN) system thus offers interconnection between 100 pairs of business users, representing a total system capacity of 15.5 Gb/s. Collisions do not occur because separate optical carriers are allocated to each connection. Obviously, network management is required to ensure proper allocation and interconnection procedures. More detailed examples will be discussed later.

Multicarrier Networks

Interconnected RENOs and BCPNs provide business users with a highly flexible and survivable network. As discussed above, the RENOs are interconnected by optical fibers using, for example, 2.5-Gb/s multicarrier transmission. Connections between a particular RENO and BCPNs can be made via other fibers using multicarriers with a lower bit rate of 155 Mb/s. As mentioned earlier, the coherent multicarrier technique is compatible with ATM. One of the BCPN field trials, as planned by the RACE project COBRA, combines coherent multicarrier techniques with ATM. Other field trials illustrate that the coherent multicarrier technique can be used to upgrade a WDM-based BCPN and to overlay an existing electrical SDH crossconnect.



■ **Figure 5.** *System application examples with the incorporation of a flexible carrier allocation. (a) A RENO is basically a crossconnect, operating at, for example, a bit rate of 2.5 Gb/s, which is complemented with an optical overlay of multicarrier heterodyne systems. Today, 16 heterodyne carriers operating at 2.5 Gb/s each can be realized, thus providing a flexible throughput of the node ranging from 2.5 Gb/s to 40 Gb/s for each fiber link, as needed. Special major events may create a need to temporarily increase the throughput of a particular link. (b) Another important reason for reconfiguring the network is the failure of a particular fiber link, caused, for example, by a broken cable. By allocating more carriers to the other links, rerouting of the communication path can be accommodated easily. (c) Business users can communicate via fibers connected to an optical star coupler. Using equipment available today, 100 channels of, for example, 155 Mb/s each can be implemented. The total system capacity is thus 15.5 Gb/s. Collisions among different connections do not occur if the optical carriers are allocated in a proper way. The configuration is thus a multiple-access system with high capacity and flexibility.*

Technology Progress

Progress and the state of the art will be discussed in this section in order to provide an overview of the tools available today for the realization of flexible multicarrier systems. In the next section, we will proceed to a more detailed description of laboratory demonstrators and field trial plans in the area of RENOs and multiple-access business systems.

At the beginning of heterodyne multicarrier system experimentation, it was uncertain whether or not semiconductor lasers suitable for the development of engineered and reliable systems would ever become available. Over the past few years, remarkable progress has been achieved in the development of dedicated lasers for the 1550-nm wavelength region. This progress is related to the achievement of high optical output powers, a considerable decrease of laser linewidths, high stability and reliability, and, last but not least, increased tuning ranges.

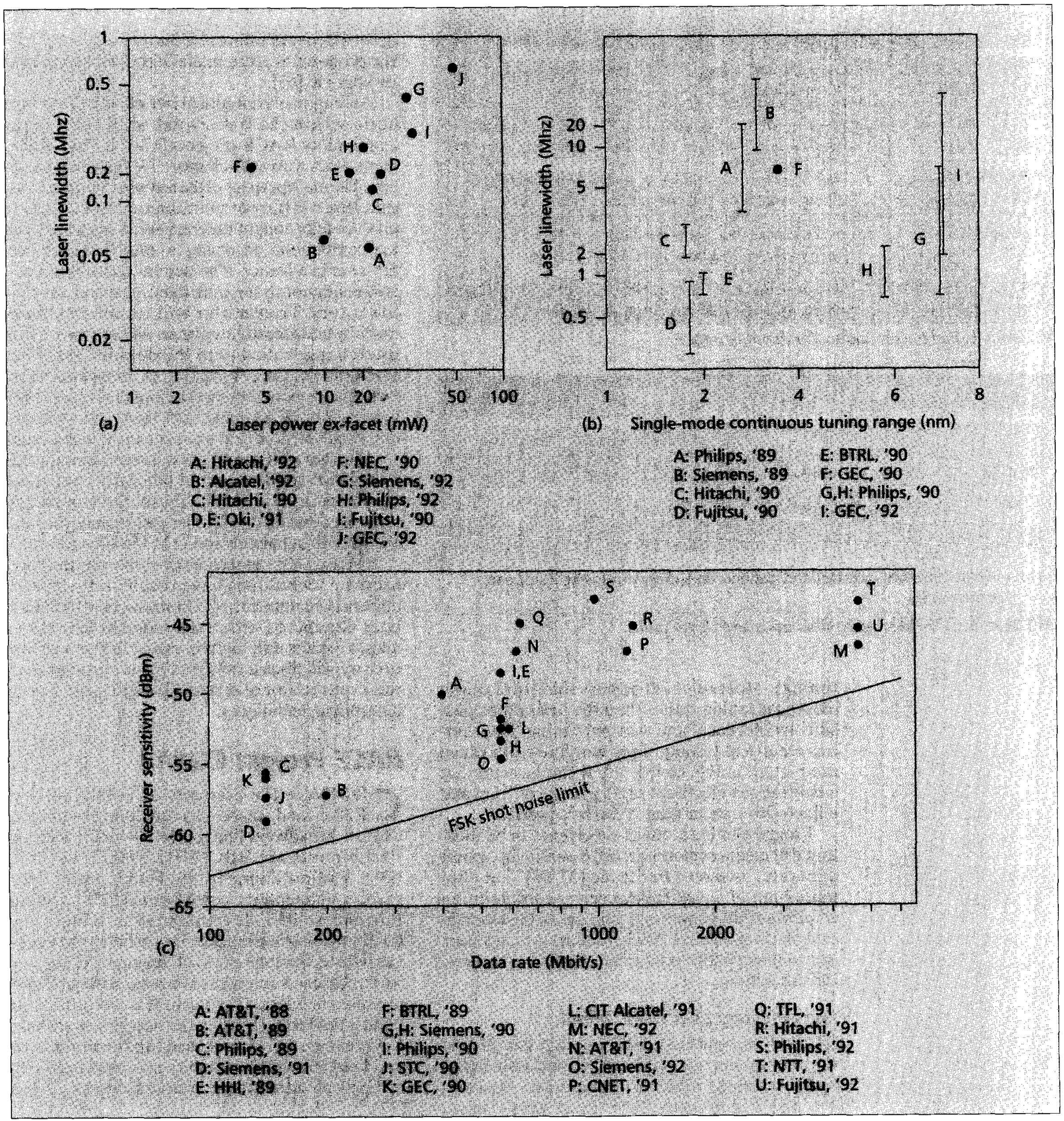
A very important feature of lasers for heterodyne multicarrier systems is their long-term stability. It may be stated that experience gained by many laboratories has indicated that laser long-term frequency stability is much better than originally expected. Bellcore, for example, has measured the absolute frequency of 11 lasers, used in a 16-carrier system, over a period of 16 months [16]. Results show that it is possible, by controlling only the laser package current and temperature, to stabilize transmitter laser frequencies to within about 200 MHz over a period of more than six months without using optical spectrometers or absolute frequency reference for feedback. Remeasurement of six lasers after a 16-month period showed a change of less than 375 MHz for any of the six lasers.

Another important achievement in the area of lasers is the possibility to order transmitters as well as tunable LO lasers from different manufacturers with accurate specifications set in advance. That result has been achieved in one of the RACE projects, carried out in the period 1988-1992 [17-19]. Three manufacturers — Plessey (now GMMT), Siemens, and Philips — successfully made fully compatible transmitters and tunable LO lasers, which were incorporated in an engineered 10-channel heterodyne broadcast system.

It is encouraging to see that many groups have contributed to the progress, as illustrated in Fig. 6. The developments are thus supported on a broad basis, worldwide. Many laboratories have also developed engineered heterodyne multicarrier systems, and several field trials have been carried out [13, 20].

Transmitters and Receivers

One of the most common modulation formats used in optical heterodyne systems is frequency shift keying (FSK). Modulation of the transmitter laser frequency can be obtained simply by modulating the current through the semiconductor laser. One of the requirements for a directly modulated laser is that its frequency spectrum (linewidth) be sufficiently narrow under all modulation conditions for the intended system. Principal parameters for a direct frequency-modulated (FM) transmitter laser are therefore linewidth, FM response, and output power. Linewidth and



■ **Figure 6.** *Diagrams illustrating progress in heterodyne transmitters and receivers. It can be seen that many groups worldwide contributed to the progress. (a) Semiconductor lasers incorporated in heterodyne systems must have a narrow spectrum (linewidth). The results shown in the diagram demonstrate that narrow linewidths of less than 1 MHz can be maintained even at high output powers of more than 50 mW. (b) The narrow linewidth must be maintained for tunable semiconductor LO lasers as well. Linewidths below 20 MHz have been demonstrated for tuning ranges of around 7 nm. (c) Heterodyne receivers have been built for field trials using data rates up to 2.5 Gb/s, showing a performance close to predicted limits.*

power results obtained for semiconductor lasers are shown in Fig. 6a [21-29]. The FM response is commonly adequate for the applications under consideration; Fujitsu reported a response range of 100 kHz to 10 GHz while the linewidth of the same laser was 0.49 MHz at 38 mW ex-facet output power [21].

The performance of a heterodyne multicarrier receiver can be characterized principally in terms of tuning range, sensitivity, and minimum optical channel spacing. A key element in the receiver is the LO laser, and the important parameters of this device are the tuning range (preferably continuous), linewidth, and output power [30]. Continuous tuning is clearly preferred, because in that case it is possible to tune the heterodyne receiver to any incoming signal frequency within the given range. Considerably higher tuning speeds can be obtained by adjusting laser current or currents (electrical tuning) than by adjusting laser temperature (thermal

Year	Bit rate	Features
1990 BT	622Mb/s DPSK,FSK	Two channel tests, via field and undersee fiber. Booster and in-line OAs tested.
1991 AT&T	1.7 and 2.5 Gb/s FSK	One month 1.7 - Gb/s test via 38km concatenated field fiber. 1.7 and 2.5 Gb/s laboratory tests with OAs.
1991-92 NTT	2.5 Gb/s CPFSK	1000-km installed fibers, eight coherent repeaters, three booster OAs. One year long-term tests.
1991-92 RACE	10 x 140 Mb/s FSK	10 channel TV distribution for more than a year continuously. Field tests in COBRA project.
1992 TFL	636 Mb/s SF-FSK	Real telecommunications traffic via 157 km submarine cable. Bidirecitonal operation for 90 days.

■ **Table 1.** *Field trials and major demonstrators.*

Type	Functions	Goal 1994	Goal 1995
RENO	2.5 Gb/s RENO-H	Laboratory trial	Field trial
BCPN	2.5 [illegible]	[illegible]	Field trial
BCPN	155 Mb/s with ATM	Field trial	
BCPN	140 Mb/s video distribution	Field trial	

Note: Goals 1995 are optional and depend on support from the European Community

■ **Table 2.** *COBRA project: field trials and demo plans.*

tuning). Most relevant papers therefore quote electrical tuning rather than the total range possible by electrical and thermal tuning. Continuous electrical tuning range and linewidth range are plotted in Fig. 6b [31-36]. It can be seen that a continuous electrical tuning range of 7 nm and a linewidth smaller than 20 MHz is possible.

Progress in heterodyne receivers can be illustrated by means of plotting receiver sensitivity against data rate, as shown in Fig. 6c [37-55]. The shot noise limit of a particular receiver configuration employing FSK is given for comparison. Results indicate that, at present, 2.5-Gb/s heterodyne receivers can be made with a performance close to theoretical predictions.

Engineering and Field Trials

Heterodyne transmission technology has left the stage of experimental work on the optical bench and reached a stage where engineered systems and field trials come to the fore. These results mean that all key parts can be manufactured by many suppliers, lasers required for the systems can be made on specifications set in advance, and the relevant electro-optical devices can be made and packaged to allow continuous system operation extending over long periods. A review of field trials and engineered demonstrators that have been operated over extended time periods is given in Table 1 [17-19, 56-65].

Most experiments listed in Table 1 deal with point-to-point links. Optical amplifiers (OAs) have been incorporated in some of the tests. Those amplifiers, in combination with the superior sensitivity of the heterodyne receiver, allow for coverage of longer repeater spans. The one-year field experiment conducted by Nippon Telephone and Telegraph (NTT) has recently been successfully concluded. A multicarrier heterodyne system operating at a bit rate of N x 2.5 Gb/s was proposed as a future candidate for system capacity upgrade [66].

An engineered multicarrier demonstrator was built within the framework of the European Community RACE projects [17-19]. That experiment deals with a 10-channel TV distribution system. The main purpose of the test was to demonstrate that three different manufacturers are able to produce fully compatible engineered equipment and key components according to interface specifications set in advance. The demonstrator was operated continuously for more than a year and was open to visitors. Transmitter and receiver modules made by the three different manufacturers were fully interchangeable due to the detailed interface specifications agreed to in advance. Equipment taken from that demonstrator will be implemented in a follow-up RACE project, "COBRA." We will discuss details of those field trial plans in the next section.

A further multicarrier test was recently conducted by NTT. A shelf-mounted laboratory setup for the demonstration of a 128-channel heterodyne system was described [67]. The system incorporates 16 x 622 Mb/s channels and 112 x 156 Mb/s channels.

The results just discussed illustrate that heterodyne techniques have reached the level of industrial manufacturing. Until now, field trials have been conducted within the scope of long transmission spans and high bit rates. In the next section, we will discuss field trial plans aimed towards the exploitation of system flexibility offered by heterodyne techniques.

RACE Project COBRA

COBRA is the acronym of RACE project R2065, and stands also for strategies towards a future broadband fiber optic network in Europe. Participants are BBC, HHI, IMEC, GMMT, GPT, Philips, Siemens, the Dutch postal, telegraph and telephone commission (PTT), and the Portuguese PTT. It is intended to achieve this goal by the possible introduction of heterodyne multicarrier technologies into all segments of the network, namely the core, the access, and the customer premises network. Obviously, it is not possible to build a field trial covering the network as a whole. Key areas are therefore selected and demonstrators and field trials will be built to show the feasibility of the proposed technique in those network segments [17].

The core network of COBRA is based on the RENO concept. The RENO experiment will show that it is possible to upgrade existing 2.5-Gb/s crossconnects to a version that offers a flexible throughput of N x 2.5 Gb/s as needed by traffic demand or for survivability requirements.

For the BCPN, three different types of business users were selected for the experiments. The BBC studios represent an environment where multiple-access communication using very high bit rates is necessary. Very high bit rates are essential here because of the need to use uncompressed format for TV and high-definition TV (HDTV) signals. The system consists basically of a multicarrier multiple-access system using a bit rate of 2.5 Gb/s/optical carrier. A system incorporating the WDM technique (Fig. 4) is being incorporated at present, and the introduction of heterodyne multicarrier systems in this environment will be a good example for the hierarchical view presented in Fig. 4. The Dutch PTT is currently operating a field trial for business subscribers, using direct detection optical techniques. Incorporation of a multicarrier heterodyne system in that environment will show how this technique can complement existing techniques. A typical feature of this system is the use of variable-bit-rate services, and in this case, heterodyne techniques and ATM [10, 11] will be combined in a field experiment for the first time. The Portugese PTT (CET) will test the multicarrier system in an environment in which continuous-bit-rate services are typical. The setup will resemble a video conferencing configuration, connecting professional users who need to discuss high-quality video information.

The access network is not covered by the COBRA project but this particular area has been covered in a previous RACE project, "CMC" [17-19, 71, 102]. Engineered equipment taken from that project will be implemented in the COBRA field trial setups. An overview of the demonstrator plans is presented in Table 2.

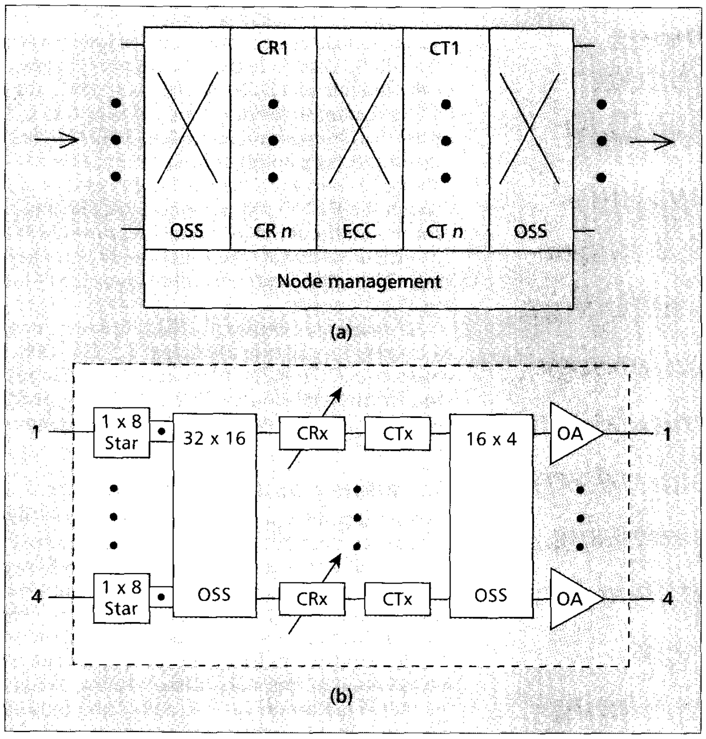
The RENO Demonstrator

The basic outline of a RENO is shown in Fig. 7a. As discussed before, the core of the RENO may be an existing electrical crossconnect (ECC) with optical fiber connections to other crossconnects. Each fiber of the existing crossconnect may support one connection at 2.5 Gb/s. Within the crossconnect, electrical switching and routing is performed at much lower bit rates, and data is demultiplexed and multiplexed at the outputs and inputs of the crossconnect to and from a level of 2.5 Gb/s.

According to the RENO concept, all 2.5-Gb/s inputs and outputs of the ECC are connected to a pool of tunable heterodyne receivers (CRs) and tunable heterodyne transmitters (CTs). An optical space switch (OSS) module is inserted between the heterodyne units and the optical fibers. Using the OSS modules [69, 70], it is possible to connect the outputs of N heterodyne transmitters to just one of the M output fibers, which, in that case, will accommodate a multicarrier transmission of Nx2.5 Gb/s. Note that the optical switches may switch rather slowly, since they are not used to switching data packets in this case. The same option is present at the input side of the RENO; one of the M input fibers carrying an Nx2.5-Gb/s multicarrier signal can be coupled by the space switch to N heterodyne receivers. The node management has the important task of controlling the optical space switch and allocating the optical carriers for the heterodyne receivers and transmitters.

We note here that the pool of heterodyne modules will not contain M x N receivers and transmitters. It is assumed that a worst-case situation requiring a maximum capacity will never occur on all fiber links simultaneously. The dynamic allocation of optical frequency carriers opens the way towards the realization of very-high-capacity connections as needed, without the necessity of constructing a network built for worst-case situations on all links simultaneously.

A full-size demonstrator, which also includes electrical switching, routing, and networking at lower levels than the optical transmission bit rate, will require a large amount of effort and is therefore beyond the scope of the RACE project. The RACE demonstrator will therefore focus only on the novel features of the heterodyne multicarrier overlay. A management part capable of controlling the optical space switch and the allocation of optical carriers will be included. It is clear from the considerations given earlier that the overlay can be used to complement an existing electrical crossconnect. The configuration of the RENO demonstrator is outlined in Fig. 7b.



■ **Figure 7.** *The general configuration of a RENO and the particular configuration to be used in the RENO demonstrator of the European Community RACE project COBRA. (a) Functional block diagram of a full-size RENO. The block in the center of the figure is an existing ECC. Without the heterodyne equipment overlay, such ECC nodes may serve in an optical network operating at a standard bit rate of 2.5 Gb/s. Each ECC node thus has optical fiber inputs and outputs, each supporting one 2.5 Gb/s connection. The transmitters and receivers used for the ECC are common, commercially available direct detection types. In the RENO configuration, the outputs of the ECC are connected to a pool of heterodyne CRs and CTs. The optical inputs of the receivers and optical outputs of the transmitters are routed by OSSes to the optical fibers. Each fiber can thus be allocated any number of optical carriers between 1 and* N. *(b) The RENO demonstrator planned by the RACE project COBRA. The demonstrator will concentrate on the heterodyne overlay only; a full-size RENO is beyond the scope of the project. The RENO demonstrator will have four fiber inputs and outputs, and the maximum number of carriers to be allocated per fiber is eight. The maximum throughput per fiber is therefore 20 Gb/s. The pool of heterodyne receivers and transmitters consists of 16 modules. It is assumed that a worst-case situation will never occur on all fiber links simultaneously.*

The RENO will consist of a pool of 16 2.5-Gb/s coherent transmitters and receivers, and eight of the 16 tunable receivers can be allocated to each of the four input fibers. It is therefore assumed that a maximum throughput of 20 Gb/s may be required on a fiber at a particular time, but never simultaneously on all fibers. At the receiver side, one to eight optical power dividers and a nonblocking OSS will be used to realize the proper allocation of the tunable receivers. At the transmitter side, all 16 coherent transmitters are connected to a 16 x 4 switch with broadcasting capability [68]. An advantage of this transmitter configuration is that distribution is possible. The total demonstrator will contain the RENO just described and four smaller-size satellite RENOs. That configuration will be sufficient to show the functionality of a network. The optical carriers will be in the 1550-nm wavelength region.

As mentioned earlier, the RENO can be used to overlay an existing electrical 2.5-Gb/s SDH crossconnect. The RENO demonstrator will be provided with SDH-compatible interfaces, and a field test is included as an option in the COBRA project for 1995.

The Business System Demonstrators

As discussed in a preceding section, the BCPN systems consist of fiber links connected to an optical star network. Optical star networks are available today, and different configurations can be constructed using a few basic modules [75-80]. The purpose of these demonstrators is to show that heterodyne multicarrier techniques can be incorporated to upgrade existing systems and that the technique can be used to complement other methods. Two examples will be discussed in the next section.

The Dutch PTT Demonstrator — The demand for broadband connections will arise initially in BCPNs. That need is among others, related to the development of all kinds of (interactive) video services and data communication. High-quality video is required in medical environments where moving pictures must be discussed or analyzed in detail. Another environment where high-quality video is required is the industrial factory environment. Industrial processes require accurate monitoring and the quality of the video material must allow detailed analysis at a later stage, if required. High-quality video pictures must remain uncompressed to allow processing without loss of information.

Among technical solutions, heterodyne multicarrier technology may be considered very promising, as it combines high sensitivity, high capacity, and high flexibility.

Among many technical solutions, heterodyne multicarrier technology may be considered very promising, as it combines high sensitivity, high capacity, and high flexibility. These advantages can be exploited in the design of a network capable of fulfilling all future demands of business customers. The feasibility of multicarrier heterodyne transmission in BCPNs and the testing in field environments are the main goals of the 155-Mb/s PTT demonstrator. ATM will be used to multiplex audio, video, and data. The use of ATM will allow a variety of multimedia applications.

In Fig. 8a, the scheme of the PTT demonstrator is shown. The topology inside the BCPN is based on a passive optical star. Five heterodyne transceivers at various locations are able to communicate at several carriers. Moreover, connections with the outside world are possible. These connections will be realized over the public network via the PTT local exchange (LEX). In the BCPN-LEX link, an OA is introduced to compensate for the fiber attenuation and the tree-splitting losses in the LEX.

Basic functions of network management will be provided: optical carrier management, call control, security functions, and maintenance. In order to have full isolation between traffic and signaling, a separate communication medium, the overlay network, is incorporated for signaling between the LEX and the subscribers. The overlay network, which operates at 1300 nm, is separated by WDM components from the heterodyne carriers, which operate in the 1550-nm wavelength region. An ATM switch will be present in the LEX for the routing of traffic on the various heterodyne carriers. By combining ATM, WDM, and heterodyne carriers, the flexibility of the network can be optimally exploited.

The combination of all the aspects just discussed must result in a realistic and complete approach towards a flexible high-capacity network, suitable for fulfilling all the broadband demands of future business subscribers. The demonstrator will be compatible with existing standards for ATM and 155-Mb/s SDH.

The BBC Demonstrator — The BBC is a typical broadcaster that requires a highly flexible BCPN with multigigabit capacity for use within its studio centers for making television programs. A passive star optical network combined with either WDM and/or multicarrier heterodyne techniques potentially offer many advantages with the advent of digital video processing and HDTV. Note that uncompressed digital video signals are required.

The BBC is planning to conduct a field trial experiment with WDM, and detailed performance tests will be carried out to discover whether or not the multicarrier heterodyne hardware will work in the WDM network. Heterodyne multicarriers will be incorporated in a spare 4-nm WDM channel which has a central wavelength of 1552 nm. Heterodyne transmitters and receivers will be interconnected via an optical star coupler, as shown in Fig. 8b. The heterodyne transmitters and receivers will be used to interconnect HDTV cameras, HDTV monitors, and professional videotape recorders. The transmission bit rate on each heterodyne carrier will be 2.5 Gb/s, and the experiment will start with three heterodyne carriers.

The long-term goal of the demonstrator will rely on:

- The use of a passive optical star network.
- All signal routing carried out by optical tuning of the receivers.
- The assignment of one optical carrier per signal.
- The need for several hundreds, possibly several thousands of carriers eventually.
- The use of components with common specifications.

The BBC demonstrator is thus aimed at showing the increased capacity and routing flexibility of heterodyne multicarrier networks over other types of optical networks for transporting studio-quality TV and HDTV signals (> 1 Gb/s).

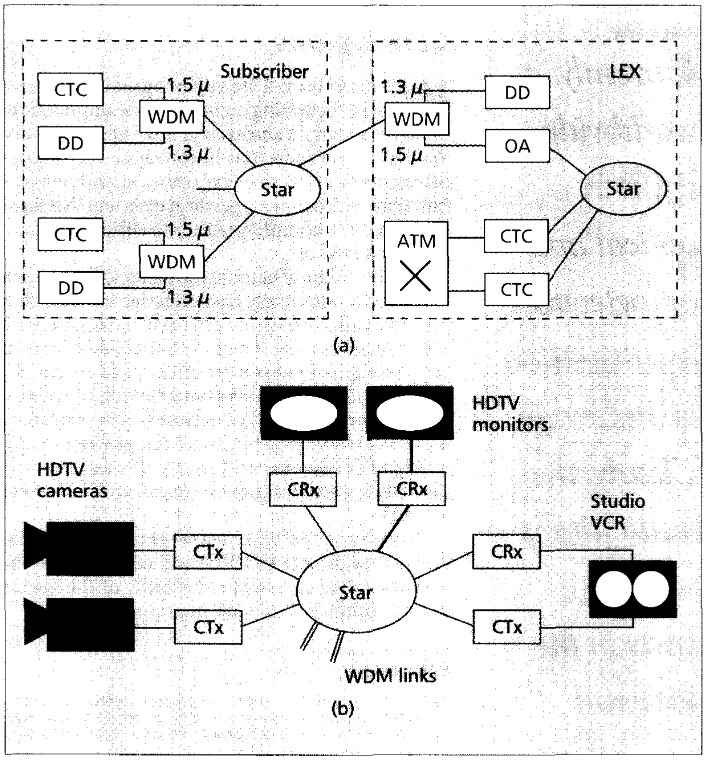
Economic Aspects

The evaluation of economic aspects of heterodyne multicarrier systems is an important part of the work within the COBRA project. In order to allow a comparison between heterodyne multicarrier systems and other types of systems, one must select a particular functionality. In the analysis, key functionalities of the demonstrators will be simulated using different technologies. Cost comparisons will sometimes rely on estimations because specific performance targets may not exist in practice at the present time. Examples are crossconnects with a throughput of 10 Gb/s/fiber. As discussed earlier, that throughput can be achieved by using bit rates of 10 Gb/s or by using a four-channel multicarrier system with a bit rate of 2.5 Gb/s/channel.

First results of the evaluation already indicate that heterodyne multicarrier systems may be an attractive solution in many areas. Details will be provided in future reports.

Currently, a worldwide effort in optical and optoelectronic integration is underway. Clearly, the main aim is to reduce costs in the long run, in much the same way as integration has worked for electronic circuits. Over the last couple of years, several companies have demonstrated [81-97] the integration of essential parts of the heterodyne receivers, in either a monolithic or hybrid way. Whether and how soon this will lead to cost reduction is very difficult to estimate, since we are at the beginning of the learning curve in this field.

An achievement that also contributes to cost reduction is the availability of mature modeling tools for heterodyne systems and related components [98-101]. Experience with the use of these modeling tools in the RACE projects has demonstrated that these models are accurate and that they can significantly reduce the number of hardware tests required in the course of the design of systems and components.



■ **Figure 8.** *Examples of the BCPN system trials of the European Community RACE project COBRA. (a) Outline of the Dutch PTT system trial. The BCPN consists of heterodyne transceivers (CTCs) which are connected to a passive optical star. Connections to the outside world are realized over the public network via a PTT LEX. ATM will be used to multiplex different types of services, and a variety of multimedia applications will be possible. Heterodyne optical carriers operating at 155 Mb/s in the 1550-nm wavelength region will be separated by WDM devices from an optical direct detection overlay operating at much lower bit rates in the 1300-nm wavelength region. The overlay network will be used for network management and control purposes. An OA is included in the BCPN-LEX link to compensate for the fiber attenuation and tree-splitting losses in the LEX. The system concept is based on full-scale operation with the incorporation of more than 100 heterodyne transceivers. (b) Outline of the BBC system trial. The heterodyne multicarrier system test will be conducted in an existing WDM network infrastructure. Heterodyne multicarriers, with a bit rate of 2.5 Gb/s each, will be incorporated in a spare 4-nm WDM channel with a central wavelength of 1552 nm. The system will be used to interconnect HDTV monitors, HDTV cameras, and studio-quality VCRs.*

Comparison with Direct Detection Methods

A detailed comparison between optical heterodyne systems and optically preamplified direct detection systems indicates that the two schemes can have equivalent performance [2]. In that case, however, the preamplified direct detection receiver has to be provided with a polarization filter and means to handle the polarization state of the incoming optical signal. Both schemes therefore contain similar functional components and modules. One important difference is that, currently, optical amplifiers based on Erbium-doped silica fibers (EDFAs) have a limited band of about 30 nm in the 1550-nm wavelength region, while heterodyne receivers with similar performance are not hampered by restrictions imposed by such special components. In addition, the EDFA gain within this band of 30 nm may show nonuniformities [103, 104], leading to the need to compensate the attenuation budget of separate WDM channels within that band. Heterodyne receivers can be realized in any wavelength range covered by available semiconductor lasers. This is one of the reasons why the operator of the TV studio mentioned earlier is considering upgrading a WDM-based BCPN with heterodyne multicarrier techniques.

An important difference in the case of multicarrier or multiwavelength transmission is the performance of the devices used for tuning and selecting. In WDM systems, channel selection can be performed by means of a tunable optical filter. A survey of the existing tunable optical filters illustrates that such devices can be made to have a high selectivity, a large tuning range, or a fast tuning speed [102]. However, it is difficult to realize an optical tunable filter that can combine all these properties in one device. It is much easier to combine selectivity, large tuning range and high tuning speed in heterodyne receivers. Semiconductor lasers can be tuned very rapidly and tuning ranges of more than 7 nm (continuous) and 30 nm (not continuous) have been reported by many. The filtering function in heterodyne receivers is performed by electrical means in the IF domain. It is therefore much easier to realize filters with a sharp profile and adequate far-off blocking properties. A multiwavelength transport network concept employing both WDM and heterodyne techniques is being studied in the RACE Phase II project R2028 MWTN [103]. The results of that project will also contribute to the understanding of how different multicarrier or multiwavelength techniques can be implemented in the most efficient way.

Currently, a worldwide effort in optical and optoelectronic integration is underway. Clearly, the main aim is to reduce costs in the long run.

Conclusions

We have seen a steady progress in heterodyne technology, and the first applications in high-capacity transmission links are underway. We have also seen that heterodyne technology offers many attractive transmission and network functions with excellent performance, and that these functions are complementary to other technologies already in use.

The flexibility of heterodyne multicarrier systems make them potentially cost-effective because they provide functionalities difficult to realize with other technologies. The heterodyne multicarrier technology provides attractive features for the realization of survivable and flexible core networks. Further cost reduction will be obtained from electronic and photonic integration in heterodyne receivers, and that will ease the way towards implementation in broadband subscriber networks.

Results of the demonstrators and field tests planned by project COBRA will contribute to the understanding of how the flexibility of the system can be optimally exploited in practice.

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Biography

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The heterodyne multicarrier technology provides attractive features for the realization of survivable and flexible core networks.