COSNET—A Coherent Optical Subscriber Network

Ad C. Labrujere, M. Oskar van Deventer, Oscar J. Koning, Johan P. Bekooij, Antonius Han Hiong Tan, Gert Roelofsen, Martin K. de Lange, Jean-Paul Boly, J. Anita H. W. Berendschot-Aarts, Cyriel P. Spruijt, Maarten F. L. van Nielen, Rob F. M. van den Brink, Kees M. de Blok, and A. Kees van Bochove

Abstract—A complete coherent multi-channel system, designed for application in the local loop is presented. The concept and the technical realization of a uni- and bi-directional system in a laboratory demonstrator are described. The realized network control, including frequency management of the bi-directional channels, and network security are discussed. Attention is paid to the evolution scenario from a narrow band to a complete broad-band system. All aspects are integrated in a demonstrator, which is capable of supporting a large number of narrow-band and broad-band distributive and communicative services. Several novel technical solutions (for frequency management, data induced polarization switching (DIPS), high-speed encryption and network signalling) are presented.

I. INTRODUCTION

COHERENT detection has three well known advantages over direct detection techniques: channel selective detection enables high density multichannel transmission over a single fiber, the higher sensitivity compared to present standard direct detection receivers can be used for network expansion, and the tunability of transmitters and receivers introduces a high degree of flexibility. These advantages can be explored in all levels of networks, but one of the most challenging is the introduction of coherent multichannel (CMC) transmission in future local loop networks to fulfill all high bandwidth requirements of residential and business subscribers [1]. In this paper the concept of such a coherent system and the realization of a laboratory demonstrator at the Dutch PTT Research Laboratories are presented. This demonstrator has been in operation for more than 12 months (since December 1991). The demonstrator not only shows coherent technology, but includes as well a number of distributive and communicative narrow-band and broad-band services, a high-speed encryption system, and a network control system, including optical frequency management. This is the first time that such a complete demonstrator based on coherent transmission is reported.

The concept of the Coherent Optical Subscriber NETWORK (COSNET) is based on the assumption that there will be a growing demand toward broad-band services in future local loop networks. These services can be differentiated into distributive services (e.g., digital HDTV distribution), and communicative services (among others high quality video retrieval, and videophony). In the COSNET-concept both kind of services are provided from the local exchange (LEX) over

Fig. 1. Network topology of COSNET.

a passive network to residential subscribers (see Fig. 1). In order to demonstrate the intrinsic differences between the two classes of broad-band services, different technical approaches have been adopted. In Section II the concept and the optical transmission techniques are discussed extensively.

It can be expected that broad-band services will be introduced gradually, and therefore they must exist in parallel to older narrow-band services. For this reason, we have aimed at the demonstration of the evolution of a narrow-band network up to a broad-band network. By means of coarse wavelength multiplexing technology we have reserved the 1.3 μm window for narrow-band ISDN services using direct detection technology and the 1.5 μm window for broad-band services using coherent technology. In Section II an extensive technical description of the coherent transmission technology is given, whereas the evolution strategy of coherent systems in local loop networks is treated in Section VI.

In a shared network like COSNET, all information can be received by all subscribers, including those for whom it is not intended. A great deal of attention has therefore been devoted to an adequate security system for the broad-band traffic. The approach followed is based on user authentication and high speed data encryption. A description of the security aspects is given in Section III.

Proper network operation requires the exchange and processing of control information. During call establishment, signalling information is exchanged between the local exchange (LEX) and the subscriber for the allocation of frequencies and the control of security procedures. All signalling information is exchanged on the N-ISDN D-channel, for which an extension of the ISDN-protocol has been developed. The signalling procedure is described in more detail in Section IV and Appendix I.

The COSNET-concept provides a wide range of possibilities to support all kind of narrow-band and broad-band services.

Manuscript received June 26, 1992; November 19, 1992.

The authors are with Royal PTT Nederland N.V., PTT Research, St. Paulusstraat 4, 2264 XZ Leidschendam, the Netherlands.

IEEE Log Number 9207723.

0733-8724/93\$03.00 © 1993 IEEE

The concept allows for transmission of many channels for both distributive and interactive services. In the demonstrator, both classes of broad-band services based on digital video transmission are integrated with narrow-band ISDN services. Detailed information on the demonstrated services is given in Section V.

II. OPTICAL TRANSMISSION

Several topologies are possible for an optical transmission network: ring, bus, transmissive star, reflective star, tree, etc. Studies have shown that the optimal topology for a broad-band distributive network is based on a passive star [2]. Each output port of the star in the LEX is followed by a tree in the field (a distribution point) for distribution of the signals. For communicative services in a subscriber network the optimal topology is based on a tree-tree configuration. One tree is used to multiplex all transceiver signals at the local exchange, while the second tree in the distribution point is applied for distribution/contribution of all signals to/from the subscribers.

The topology in the COSNET demonstrator is based on an optical star in the LEX, followed by passive trees (see Fig. 1) [3]. The signals of the coherent transmitters for the distributive services and transceivers for the communicative services are multiplexed in a (16×16) transmissive star at the local exchange. The coherent signals (at a wavelength of 1536 nm) are multiplexed with the signals of the direct detection transceiver (at 1310 nm) by means of coarse wavelength multiplexing. One of the output ports of the transmissive star is used for the frequency management of the coherent channels. All signals are transmitted to/from the subscribers over 2.5 km of cabled fiber and a tree network [3]. The power budget, the signalling scheme (time delay) and the clock recovery of the bi-directional coherent system allow for longer transmission lengths (up to some tens of kilometers) without disturbing the overall system performance.

At the subscriber site, a wavelength demultiplexer splits the narrow-band and broad-band signals. The subscribers in a COSNET system have a transceiver for narrow-band ISDN services, a receiver for coherent TV reception and a coherent transceiver for broad-band communicative services.

The narrow-band ISDN transmission system in COSNET is capable of carrying up to 32 bi-directional (2B+D) communication channels with a bandwidth of about 75 kHz each. AM-subcarrier multiplexing [4] with 64 different frequencies is used: 32 for the downstream and 32 for the upstream direction. In the downstream direction all channels are sub-carrier multiplexed on a single optical carrier. In the upstream direction, the signals of the 32 subscribers are multiplexed in the distribution point (see Fig. 1). In the demonstrator, high power (0 dBm) single-mode intensity modulated laser diodes are used as transmitters, while each optical receiver is based on a PIN-photodiode (sensitivity -37 dBm). In principle, the upstream transmitters can have a lower output power to achieve the same power budget as for downstream traffic. This is due to the higher applied modulation index (100%), compared to the downstream channels (3%).

In the following subsections details on the realization of the coherent systems are given. The frequency management

used to control the wavelength of all lasers, is discussed, followed by a description of the coherent techniques used for TV-distribution and communicative services. Some of these aspects have already been reported in [3].

A. Frequency Management

A coherent multichannel system requires careful management of all channels in the network [5]. For the frequency management in COSNET, four basic functions can be distinguished. Firstly, active frequency stabilization of the optical carriers is required in high density multiplexed systems. In a coherent system, this is often necessary as the tuning range of the local oscillators (LO's) is limited. Secondly, frequency management is required during a system start-up procedure. This is not only necessary during installation of the system, but also after system break-down or system adaptation (for example, adding new channels to the original comb). The third function is the fault management. Malfunctioning lasers must be excluded from the system, as they can cause interference on other channels. The fourth function deals with flexible allocation of channels and the supervision of the tuning of the coherent lasers to new wavelengths. These four functions and the implementation in COSNET are described more extensively below.

1) *Frequency Stabilization:* All laser frequencies in COSNET are stabilized actively. For control of the lasers a multi-step mechanism is required. The first step is to monitor and stabilize the frequencies of the transmitter lasers at the LEX. This is performed by a so-called supervisor unit. The stabilized comb of channels is transmitted to all subscribers. The local oscillator lasers at the subscriber site are stabilized relative to a carrier within the comb by using offset locking techniques [6]. This principle is both applied for the distributive and the communicative services. The subscriber transmitter laser used for the broad-band interactive services is on its turn offset locked to the corresponding LO. This so-called "tandem-locking" results in a pair of upstream and downstream channels for the communicative services. The fourth step is that the local oscillators at the LEX used for broad-band communication are locked relative to the LEX transmitter lasers.

In this way all coherent LO and transmitter lasers are stabilized either directly or indirectly by the frequency supervisor unit. The supervisor unit is a computer controlled heterodyne spectrum analyzer and consists of a current controlled DBR scanning laser, a polarization diversity receiver (1 kHz–100 MHz IF-band) and a Fabry–Perot interferometer (see Fig. 2). The spectrum is measured by monitoring the beat signal of the scan laser and the comb of channels during tuning. An interferometer ($\text{FSR} = 5$ GHz; $\text{Finesse} = 20$) is used to determine the scan nonlinearity. The scanning laser is tuned over 130 GHz every 10 s. The sensitivity of the receiver is -40 dBm at a SNR of 10 dB. The observed channel frequencies are compared with specified values in a PC. The laser wavelength is adjusted accordingly to the current/temperature-wavelength characteristic (stored in the PC).

In Fig. 3 a typical display of the frequency supervisor control computer is shown. Bottom right the interferometer trace is depicted. From this signal the relative frequency

Fig. 2. Frequency supervisor unit.

Fig. 3. Display of supervisor unit. Detailed information on the laser positions are visible on the screen.

calibration can be extracted (bottom left). The measured star output spectrum is shown in the middle while details of three detected channels can be found at the top. When active stabilization is applied, a maximum laser drift of 200 MHz is observed. For a six hour free running system, the channel drift was 500 MHz. Although this difference is not large, one can expect that for a system running for a number of years, larger frequency deviations may occur due to laser aging effects. This implies that the channel spacing in a free running system must be much larger than in an actively stabilized system.

At the subscriber site, AFC technology is applied to lock the lasers to a carrier within the comb. The overall stability of the system can be illustrated by observing the beat signal of the LEX LO and the subscriber transmitter laser. For a free running system, IF fluctuations of 500 MHz are observed. However, when the three AFC loops are closed, the fluctuation in the IF is reduced to below 30 MHz. This low value makes satisfactory performance of bi-directional traffic possible.

2) *Cold startup*: A cold startup procedure has been implemented in the supervisor unit, and consists of the following steps. Firstly, each transmitter laser in the LEX is coarsely tuned to the desired channel frequency by using a look-up table, after which it is optically switched to the network (by a mechanical on/off switch) and the position is recorded by the

heterodyne spectrum analyzer. Secondly, the supervisor unit controls the fine-tuning of the lasers to their exact channel frequencies. The transmission of signals then starts.

The laser tuning procedure at the subscriber site consists of three steps. Firstly, information on the channel frequency must be available. For distributive services this is simply achieved by using a look-up table, as the distributive lasers continuously transmit on a predefined wavelength. For the bi-directional system, a channel allocation procedure must be followed. This signalling information can be exchanged on the narrow-band ISDN channel. The second step is coarse tuning by adjustment of the laser temperature to the required channel, the temperature value being retrieved from a look-up table. The third step is fine tuning by current adjustment. This step is much faster than the second step. The AFC loop of the LO is closed if an IF signal is detected. For tandem locking of the subscriber transmitter laser the same procedure is followed. In order to prevent channel interference, the subscriber transmitter laser is switched off the network during tuning by an external switch.

3) *Fault management*: The third functionality of the frequency manager is fault management. The transmitter lasers at the LEX are continuously monitored by the supervisor unit. If the power of a transmitting laser is lower than a specified value, or if the frequency drift is too large, the lasers are automatically switched off by an external switch. It should be noted that during the operation of the demonstrator (12 months), the transmitter lasers were never switched off. At the subscriber site, the transmitter lasers are switched off if the AFC-loop is not closed. This can be caused either by too low a transmitting power, by too large a drift of the laser, or by a malfunctioning AFC. Such malfunctions is obviated by an automatic restart procedure.

4) *Channel allocation*: The fourth function of the management is the allocation of frequencies for bi-directional communication. It is only possible to have a limited number of coherent transceivers in the LEX, which must be shared by a large group of subscribers. To accomplish this, the statistical character of traffic in the local loop may be used. Flexible channel allocation in the LEX or at the subscriber site is then necessary to set up the connections. In the COSNET demonstrator, this function has been integrated in the start up procedure, and is not possible during operation. However, with a small modification of the supervisor unit software, this can be demonstrated.

B. Coherent Distributive System

One of the promising applications of coherent technology in the local loop is the distribution of digital HDTV. As this application may be required sooner than bi-directional broad-band services we have aimed at the realization of separate distributive and communicative systems. For the distributive services, we have used DFB transmitter (Tx) and local oscillator (LO) lasers, and Data Induced Polarization Switching (DIPS) causing complicated polarization handling at the subscriber site to be superfluous. This simpler technique is however on the cost of a theoretical 3-dB power penalty compared to polarization control [7].

Fig. 4. Coherent distribution system with data-induced polarization switching (DIPS) and polarization scrambling.

Three coherent TV-channels are distributed from the LEX to the subscribers. The general setup of the distribution system is shown in Fig. 4. DCPBH-DFB lasers (1537 nm, 20-MHz linewidth) are used as transmitter and local oscillator lasers. The Tx-lasers are modulated in a wide-deviation FSK format (155.52 Mb/s, 1-GHz deviation, 1.5-GHz IF frequency, 100-GHz channel spacing). Manchester coding was used to avoid penalties due to the non flat FM response of the DFB lasers. For reasons of simplicity the Manchester signal was not decoded synchronously [8], but detected at the double bit rate of 311.04 Mb/s, which implies another 3-dB penalty. Data induced polarization switching (DIPS) was implemented with 180 m of highly birefringent (PANDA) fiber [7] with 2.8-ns/m birefringence, resulting in a 0.5 ns differential delay between the two principal polarizations. At the subscriber site the detected signal from the balanced receiver (noise: 20 pA/sqrtHz) was demodulated by a delay-and-multiply FSK-discriminator with 0.5 ns delay. The sensitivity of the receivers is -40 dBm. The transmitter power is -5 dBm (in fiber).

A complication of automatic frequency control (AFC) with DIPS is that the 0's or the 1's fade with polarization fluctuations. A solution is the application of a second frequency discriminator as described in [7]. However, this discriminator has frequency locking ambiguity, which makes switching between channels difficult. Instead we avoided this discriminator and applied a polarization scrambler at the Tx lasers to achieve unambiguous locking. The polarization scrambler was made of 21 m hibi-fiber (the last 21 m of the 180 m Panda fiber), wound around a piezo electrical tube (5.2 cm diameter) [10]. A piezo voltage change of 1000 V corresponds to 16 pi differential phase shift. The scrambler was modulated with a triangular wave at 50 Hz. Since the scrambling rate is faster than the AFC control speed, the effective polarization induced drift of the IF spectrum is reduced substantially.

C. Coherent Communicative System

The coherent system for bi-directional traffic is more complicated than for the uni-directional traffic. This is partly due to the principle of tandem locking: the upstream transmitter lasers are locked to the downstream channels. In order to have an acceptable spacing between these channels (in the order of a few gigahertz), narrow deviation CPFSK has been chosen as modulation format, which makes the application of DIPS less suitable. For this reason, we have chosen for the principle

Fig. 5. Coherent transceiver with polarization diversity and offset locking of remote Tx laser.

of polarization diversity, which yields the highest receiver sensitivity without the need of active polarization control [8].

In the demonstrator, one bi-directional channel has been realized. The general setup of the coherent transceiver is shown in Fig. 5. MQW-DBR lasers are used (1535 nm, 1-MHz linewidth) as transmitter and receiver lasers. The modulation format is CPFSK. Since Manchester coding was used, the transmission bit rate was 311.04 Mb/s. The IF frequency is 600 MHz, while the frequency deviation was 300 MHz. The gain-sections of the lasers are used for the CPFSK modulation and fast frequency tuning to avoid linewidth broadening.

Polarization diversity was implemented with one plasmon-type polarization splitter (type SIFAM) and three 50/50 couplers (BT&D), all in standard 9/125 fiber. Polarization of the hybrid was adjusted once with fiber loops [11] and was found to remain stable. The signal is received by two low noise (7 pA/sqrtHz) balanced receivers based on current-current feedback [12]. The receiver performance was analyzed using a calibrated synthetic noise measurement setup [13]. The signal is demodulated by two delay-and-multiply frequency discriminators with 1.7 ns delay, whose outputs are added passively. The AFC signal is again derived directly from the discriminator outputs.

For the tandem locking scheme a small fraction of the transmitter and the local oscillator laser power is split off by two 10/90 couplers, mixed in a 50/50 coupler and detected in a single detector 3 GHz bandwidth receiver (see Fig. 5). As the lasers are offset locked at 2.4 GHz the upstream-downstream channel spacing is 1.8 GHz in the IF-domain. The polarization diversity receiver sensitivity was determined to be -45 dBm. The transmitter power (in fiber) was 0 dBm. It should be noted that higher link budgets for coherent links can be expected, with values of 50-60 dBm being realistic, as has been demonstrated in more technology oriented projects like the RACE-1010 CMC-project [14].

D. Interference Between Direct Detection and Coherent System

CMC transmission can be introduced as an overlay of an existing narrow-band system. As the N-ISDN systems will be introduced without any specification with respect to future transmission technology, crosstalk between both systems must be avoided. The coherent channels contribute to the direct detection receiver mainly through the residual intensity

modulation of the coherent transmitters. The influence of the excess shot noise, resulting from the total power of the comb of coherent channels is negligible. Calculations [15] showed that the optical power per coherent channel to the direct detection receiver should be kept below -48 dBm to yield a penalty of less than 0.1 dB on the N-ISDN system. This calculation is based on 64 (155 Mb/s FSK) channels with 10% residual intensity modulation. The resulting specification for the wavelength demultiplexer depends on the optical powers of the various signals at the demultiplexer input. For the COSNET-configuration 15 dB extinction ratio is sufficient.

The direct detection system leaks through to the CMC receiver as well, although it is suppressed to a large extent when balanced detection is applied. Moreover, in our system the subcarrier multiplexed direct detection signals do not coincide with the IF-band of the coherent receiver. For these reasons, we did not observe any interference of the direct detection system on the CMC system.

III. SECURITY

Within COSNET a number of security functions have been introduced to offer protection against certain security threats. One of the main threats is that the information meant for one end user is, together with other information, distributed to a larger group of users. At the end user site the proper information is selected by tuning on the proper frequency. Thus, in principle, users can eavesdrop information from other users by changing frequency (even though it might be technically difficult). In the COSNET system cryptographic countermeasures against eavesdropping have been taken. A second threat, which most communication systems have in common, is illegal access by means of impersonation of a legal user, and against this threat a cryptographic countermeasure was also specified.

Based on the above considerations it was decided to specify a security system based on cryptography. The security measures can be divided in two phases. Firstly, the users are authenticated, and encryption keys are exchanged. These keys are used in the second phase, the encryption of the user data. Below these phases will be explained in detail.

A. Phase 1: Authentication and Key Exchange Phase

Every end user (A) has a secret authentication key "AUTKEY," which is also known in the LEX. If two users A and B want to set up a call, the LEX authenticates both users, by checking with a cryptographic challenge/signed response protocol that both users are in the possession of their individual AUTKEY's. The LEX then uses these AUTKEY's to encrypt a key ENCKEY, which is then sent to both users. This first phase is executed during call establishment. The exchange of encryption information is integrated in the signalling protocols.

B. Phase 2: High-Speed Encryption Phase

In this phase ENCKEY is applied by both users to encrypt user data by a key stream generating encryption algorithm. A test version of the algorithm was implemented in the demonstrator. This algorithm encrypts user data at the 155 Mb/s transmission speed of the demonstrator. A special syn-

chronization algorithm was developed to synchronize the encryption hardware on both sides of the communication link. This synchronization algorithm is based on pattern detection in the encrypted bit stream. When the pattern is detected the encryption device is re-initialized on both sides of the communication link. The information loss in case of a loss of synchronization can be tuned by varying the length of the synchronization pattern.

A hardware prototype has been built consisting of four XILINX programmable gate arrays. The design of the hardware was done using the logic synthesis modules of the ASA silicon compiler. With ASAs layout synthesis tools, a silicon chip design has been realized successfully in order to evaluate the feasibility for mass production. In the demonstrator, the user authentication procedure has been implemented, while the hardware prototype for high-speed data encryption is in the test phase.

IV. NETWORK CONTROL

Broad-band connections between two subscribers must be preceded by the exchange of signalling information. This standard procedure is necessary to establish and control the connections. For a multicarrier (e.g., a CMC) system, new protocols must be developed containing wavelength management information: so that the wavelength of the transceivers involved correspond before the actual communication starts. This implies that the LEX determines a "free" wavelength for the bi-directional connections to be set up. Upon receiving this information, both the LEX and the subscriber transceivers tune to the operating wavelength. The transceivers must be switched from the network during tuning in order to avoid interference on other channels.

The most elegant way to realize information connections between the LEX and the subscribers is by multiplexing the signalling information within the broad-band data connections. This can be realized relatively easily in ATM-based systems, however this approach has the drawback that the control channel is disconnected during tuning of the coherent lasers. This implies that errors occurring during tuning are not detected. Moreover, it is necessary that all idle transceivers in the network "listen" to a coherent control channel.

In the COSNET system, we have used the ISDN-overlay network operating at $1.3 \mu\text{m}$. This direct detection system provides each subscriber with a permanent connection to the LEX. It is simultaneously used for the provision of narrow-band services. This has the advantage that signalling information can be exchanged, even during tuning of the coherent transceivers. The signalling information is exchanged on the ISDN D-channel. In order to support the establishment of the broad-band connections, an adopted ISDN network control layer protocol has been implemented. A more detailed description is given in Appendix 1.

V. SERVICES

The multichannel nature of the COSNET concepts enables the provision of all kinds of broad-band services on each channel. In principle all kinds of services can be provided (distributive, interactive, retrieval, narrow-band and broad-band).

Fig. 6. A photograph of a subscriber set up of the COSNET system. Security monitoring and TV-reception are offered on the coherent bi-and uni-directional channels.

The coherent transmission technology has some significant large advantages for broad-band services. Among them, the huge amount of transport capacity is one of the foremost: distribution of hundreds of digital TV-channels, combined with the provision of interactive broad-band channels is possible.

Coherent multichannel transmission facilitates simple switching techniques by allocation of frequencies. On the other hand, all kind of electrical switching techniques being standardized for broad-band ISDN systems are possible. Application of ATM within each coherent channel (as a payload of the SDH frames) may be applied to use the broad-band capacity of each channel optimally. A further advantage of CMC technology is the upgradability of the network capacity without changing the network transmission technology.

For demonstration purposes, we have selected five broad-band services. These services are: high quality videophony, interactive security monitoring, digital TV distribution, and high speed LAN interconnection including video database retrieval. The demonstration of telephony over the N-ISDN channels is simultaneously demonstrated. Some of the services (videophony, video database retrieval) are implemented by an integrated use of N-ISDN and broad-band channels.

A part of the realized demonstrator is shown in Fig. 6. In this figure, the equipment of one of the two realized subscribers is shown. A PC is used for network control. Broad-band connections between two subscribers can be realized via the LEX. The right TV-screen shows broad-band-video/baby-sitting (interactive security monitoring). Other possible communicative services are videophony and LAN-interconnection with video-retrieval. Besides these services, the subscriber can receive three digital TV-channels. On the left TV-screen, one can see the reception of one of the channels. Besides these broad-band services, N-ISDN telephony is simultaneously offered.

VI. EVOLUTION PATH

The introduction of fiber in local subscriber networks can be envisaged in the near future. These networks must be compatible with present copper networks, as the services to be provided must be similar to all subscribers. For the

Fig. 7. Infrastructure of Dutch FTTH field trial (the Sloten system).

residential subscribers these services are mainly narrow-band services (POTS, or N-ISDN), and in some countries cable television. Technical field trials are performed worldwide to demonstrate the feasibility of the fiber to the home or fiber to the curb concepts. Among others, the Dutch PTT Telecom is performing a field trial in Amsterdam (the Sloten trial), in which the feasibility of digital telephony and analogue CATV transmission in FTTH concept to about 300 residential subscribers is being demonstrated [16]. The infrastructure of this system is sketched in Fig. 7. From the LEX, a 24 fiber cable is installed in a ring configuration, and directed to 6 distribution points (DP's). In each DP, 4 fibers are cut through, resulting in 8 fiber connections for the residential and business market. In this concept, the business subscribers have a (double routed) full star connection. The residential subscribers share a single fiber, which is connected to a 4 : 32 passive optic star in the DP. Three input ports of the star are at present reserved for back-up, double routing and/or the provision of future services.

Although the introduction of fiber in the local loop is purely based on present services, the almost inexhaustible bandwidth of fiber can be explored in future broad-band networks. New broad-band transmission technologies like CMC can be introduced in parallel to the narrow-band services by using wavelength multiplexing technology as in COSNET or using separate fibers. As an example, we discuss the evolution from a narrow-band toward a broad-band network on the Sloten infrastructure.

In the first phase, standard telephony (POTS or N-ISDN) is offered (see Fig. 8). These services are provided in the 1.3 μm , using direct detection techniques. In the second phase, digital TV distribution to the subscribers over the same infrastructure is possible by making use of the 1.5- μm window. Relatively simple coherent equipment must be integrated in TV-sets. In the third phase, broad-band interactive services in the local loop can be envisaged. B-ISDN based on ATM and bi-directional traffic can be offered in parallel to the distributive services in a slightly different wavelength region within the 1.5- μm window (see Fig. 8). In the last step, the network will be a complete B-ISDN system.

The multiplexing of the signals can either take place in the LEX by using wavelength multiplexers, and in the distribution point by using several fibers (see Fig. 8). The spectrum of the channels in the network are shown in the same figure. At the subscriber site, a wavelength demultiplexer is necessary to split

Fig. 8. Evolution path of a FTTH-system. Firstly, N-ISDN is offered, followed by CMC TV distribution and B-ISDN. Implementation of optical amplifiers (OA) for distributive services results in system expansion. For communicative services, the traffic density sets bounds to the network expansion.

the narrow-band and broad-band signals. The narrow-band signals can be converted directly into the electrical domain and processed further. The broad-band coherent signals must be split further optically. One branch is used to receive (and transmit) the B-ISDN channels, and the other branches for TV-reception.

The possibilities coherent optics offers in local loop networks are enormous. Starting from a power budget of 50 dB and the Sloten infrastructure, one can derive that 64 digital TV-channels (of 155 Mb/s each) can be offered to about 8000 TV-sets. The TV signals are multiplexed in a 64×64 star in the LEX, and distributed to 64×32 subscribers, each having 4 TV-connections. The ideal splitting losses are about 39 dB, but the asymmetry of the splitters, the fiber attenuation, and some system margin should be taken into account. This causes a reduction of about 11 dB in the overall power budget. By applying optical amplifiers (EDFA's) in the LEX, the number of splittings in the network can be extended by orders of magnitude (see Fig. 8). This implies that in principle a small city can be provided with TV-channels from a single head-end.

In parallel to these distributive services, a second fiber to the 4 : 32 star may be used to provide each subscriber with a full broad-band ISDN connection (155 Mb/s up- and downstream; see Fig. 8(b)). Optical amplifiers are less attractive in this concept, as they must be suitable for bi-directional traffic, and moreover the traffic density rather than the optical power budget is the limiting factor.

It is important to note that the infrastructure developed for narrow-band services (4 : 32 tree) can be applied for the coherent transmission. The difference in power budget (about 30 dB for a direct detection system, and 50–60 dB for a coherent system) does not affect the optimal infrastructure design. This is due to the necessary multiplexing (e.g., 64×64 star) in the LEX and de-multiplexing (1×4) at home. The infrastructure for narrow-band services can hence be upgraded

simply, if a transmission window of fiber is reserved for future technology. This implies that without any radical changes, the present infrastructure can be used for coherent transmission. From the operators' point of view, the infrastructure being realized on short term is able to transport future broad-band services over coherent channels. This is a necessary boundary condition for the subscriber access networks, which have an effective lifetime of about 30 years.

VII. CONCLUSIONS

In this paper we have presented a concept and the technical realization of a coherent multichannel system designed for application in the subscriber network (COSNET). The laboratory demonstrator has been in operation for 12 months. The system includes uni- and bi-directional traffic for broad-band distributive and communicative services. Both classes of services are offered by different types of technologies. The transmitters for the distributive services are DFB-lasers. DPS is used to decrease the complexity at the subscriber site. For the communicative services, narrow linewidth DBR lasers in combination with polarization diversity receivers are applied. Locking of the upstream channels relative to the downstream channels (tandem locking) is applied to realize a distributive frequency management.

The coherent system can be considered as an overlay of existing narrow-band services. This evolution scenario is implemented in the COSNET system by coarse multiplexing of a direct detection system at 1.3 μm with the coherent channels at 1.5 μm . The direct detection channel is used for provision of N-ISDN by using electrical subcarrier multiplexing techniques.

COSNET is a complete system in the sense that besides technical realization, attention is paid to network control and network security. The COSNET signalling system is based on ISDN protocols. For the broad-band services we specified new information elements as extension of the network layer protocol. All signalling messages are integrated in the ISDN D-channel.

Network security has been implemented since in a shared network system like COSNET information for a single subscriber can in principle be received by all connected subscribers. In the COSNET system, two types of security functions have been realized to prevent eavesdropping. Firstly, user authentication is performed (on the narrow-band signalling channel), and secondly the broad-band data bit stream is encrypted using exchanged encryption keys.

Although coherent transmission still is a technology of the future, it is of vital importance that it can be introduced smoothly when the demands for high quality digital services (video based services) grow. Therefore, the COSNET-infrastructure has been designed in such a way that implementation in the field is possible. The concept very well fits within the Dutch Sloten (local loop) field trial in the Netherlands. In the forthcoming years, tests of coherent transmission on this infrastructure will be performed in the RACE-2065: COBRA project [14]. The outcome of these field experiments may give more pronounced judgements on the feasibility of coherent multichannel transmission in the subscriber network.

Fig. 9. Typical sequence of signalling messages during call setup.

APPENDIX I

Signalling is the exchange of information specifically concerned with the establishment and control of connections [17]. In COSNET we concentrated on user-network signalling, i.e., the case where signalling information is exchanged between terminal equipment (TE) and local exchange (LEX). Two main functions can be distinguished in a signalling system:

1. the generation and interpretation of signalling messages,
2. the transfer of these messages between TE and LEX.

The procedures which define these functions are specified in the form of protocols.

In COSNET standardized ISDN basic rate access (2×64 kb/s for user information + 16 kb/s for signalling information) is offered to all subscribers. The ISDN signalling system [18] is employed in COSNET for the control of narrow-band services. For the control of COSNET broad-band services, the ISDN protocols were extended where necessary.

For the first main functions an ISDN protocol which defines the generation and interpretation of signalling messages [19] is specified: the so called network layer protocol. This protocol includes a specification of the order in which the signalling messages are exchanged and of the information elements carried by these messages. See for example Fig. 9 which shows a typical sequence of signalling messages during call setup. The characteristics of COSNET broad-band services show great similarity with the characteristics of ISDN narrow-band services, except for the use of a 155.52 Mb/s information transfer channel. Therefore, the ISDN protocol has been adopted for the control of broad-band services and as only extension new information elements and new values for existing information elements needed to be specified.

This means that for the control of COSNET broad-band services the sequence of signalling messages as shown in Fig. 9 still applies. The extensions to the ISDN network layer protocol allow the exchange of the following signalling information:

- the broad-band bearer capability that is requested (Setup message)
- the optical frequency that identifies a coherent channel (Setup-Ack message)
- the service type that may be used for compatibility checking (Setup message)
- the data needed for encryption and authentication procedures (Setup-Ack, Info, Connect messages)

This information is used among others for the control of laser AFC's, high-speed encryption hardware and monitor selection switches.

For the second main functions ISDN protocols which define the transfer of signalling messages [20], [21] are specified. These define a 16 kb/s signalling transfer channel which is virtually error free, the so called *D*-channel. This channel is used for the transfer of signalling messages for both narrow-band and broad-band services. In COSNET the corresponding ISDN protocols were employed unchanged.

The implementation of the signalling system is based on a ISDN development kit which consists of PC plug-in cards with on-board processor, dedicated integrated circuits and protocol software. We extended the network layer protocol software for both the TE and the LEX. In each PC which is configured as TE, the protocol primitives are passed to the human user interface software. The PC which is configured as LEX, contains protocol hard- and software for each subscriber. For the transmission over the fiber, at the fiber termination the ISDN frame structure is converted to a 120 kbaud ternary signal which is interfaced with the direct detection transmission system. This ISDN frame structure contains the *D*-channel and two 64 kb/s user information channels.

REFERENCES

- [1] A. C. van Bochove *et al.*, "Coherent transmission in the local loop," in *Proc. IX International Symp. Subscriber Loops & Syst.*, (ISSLS) 1991, (Amsterdam, The Netherlands).
- [2] A. C. Labrujere M. O. van Deventer, and O. J. Koning, "Coherent multi-channel technology in the local loop," *Int. Symp. Fiber Opt. Net. Video Commun. (Europto 1993)*, Berlin.
- [3] A. C. van Bochove and M. O. van Deventer "COSNET: A coherent optical subscriber network with bi-directional broadband channels," *16th European Conf. Optical Commun. ECOC'90* (Amsterdam, The Netherlands), paper TuP6, pp. 369-372, 16-20 Sept. 1990.
- [4] H. H. Tan, "A digital transmission system using FDM for a passive optical tree," *IEEE Workshop Passive Optical Networks for the Local Loop* (London, United Kingdom), May 1990.
- [5] J. P. Bekooij, O. J. Koning, and A. C. Labrujere, "Carrier stabilization in coherent multi-channel systems, using a comb of reference frequencies," in *Proc. OCTIMA'91*, (Rome, Italy), 1991.
- [6] O. J. Koning and M. O. van Deventer, "Frequency management for uni- and bi-directional coherent optical subscriber network (COSNET)," *18th European Conf. Optical Commun. ECOC'92* (Berlin, Germany), 1992, paper TuP 1.25, pp. 321-324.
- [7] R. Noé, J. L. Gimlett, R. S. Vodhanel, and S. Tsui, "Polarization-insensitive, 500 Mbit/s FSK transmission over 153 km by passive polarization switching," *Electron. Lett.*, vol. 25, p. 4, 1989.
- [8] P. W. Hooijmans, M. T. Tomesen, and A. van de Grijp, "Bi-phase linecoding in optical FSK heterodyne transmission experiment, without sensitivity degradation compared to NRZ," *Electron. Lett.*, vol. 25, p. 326, 1989.
- [9] R. Noé *et al.*, "Comparison of polarization handling methods in coherent optical systems," *J. Lightwave Technol.*, vol. 9, 1991, p. 1353.
- [10] G. R. Walker and N. G. Walker, "Rugged all-fibre endless polarization controller," *Electron. Lett.*, vol. 24, no. 22, pp. 1353-1354, Oct. 1988.
- [11] H. C. Lefevre, "Single mode fibre fractional wave devices and polarization controllers," *Electron. Lett.*, vol. 16, pp. 778-780, 1980.
- [12] R. F. M. van den Brink, "Optical receiver with third-order capacitive current-current feedback," *Electron. Lett.*, vol. 24, pp. 1024-1025, 1988.
- [13] R. F. M. van den Brink, E. Drijver, and M. O. van Deventer, "Novel noise measurement set-up with high dynamic range for optical receivers," *Electron. Lett.*, vol. 28, no. 7, pp. 629-631, 1992.
- [14] G. D. Khoe *et al.*, "Coherent multi carrier technology for implementation in the customer access," *J. Lightwave Technol.*, this issue.
- [15] M. O. van Deventer, to be published.
- [16] H. R. C. Tromp, H. T. Nijhuis, Y. Boomsma, and J. Bakker, "Fibre to the home in the Netherlands' proceedings of the IX international symposium on subscriber loop and services ISSLS, Apr. 1991 (Amsterdam, The Netherlands).
- [17] "Vocabulary of terms for ISDNs," CCITT Recommendation I.112; blue book 1988.

- [18] "ISDN protocol reference model," CCITT Recommendation I.320; blue book 1988.
- [19] "ISDN user-network interface layer 3 specification for basic call control," CCITT Recommendation Q.931; blue book 1988.
- [20] "ISDN user-network interface—data link layer specification," CCITT Recommendation Q.921; blue book 1988.
- [21] "Basic user-network interface—layer 1 specification," CCITT Recommendation I.430; blue book 1988.

Ad C. Labrujere was born in Haarlem, Netherlands in 1960. He received the M.Sc. degree in 1983, and the Ph.D. degree in physics at the Leiden State University in 1988.

In 1988 he has been working at PTT Research as a research staff member, where he worked on coherent optical communications systems, optical amplifiers, and nonlinear optics. He is involved with the Dutch PTT strategy for the introduction of fiber in the access network. Since 1992 he has become involved in the RACE 2065: COBRA project, aiming at the implementation of coherent multichannel techniques in application oriented environments. He is the project manager of the inter-university project "Multi-Access Optical Coherent Networks," funded by the Ministry of Economic Affairs as part of the Innovative Research Program (IOP) Electro-Optics.

Antonius Han Hiong Tan was born in Malang, Indonesia on June 25, 1952. He received the M.Sc. degree in electronics at the Technical University of Delft in 1980.

In the same year, he joined PTT Research as a research member. His major technical activities are in digital optical communications, analogue optical communications for CATV, coherent optical systems, and analogue electronic circuits in general.

Gert Roelofsen studied Discrete Mathematics at the University of Technology in Eindhoven.

He joined PTT Research in 1986 and works in the area of cryptology and security. His activities include the design of security systems and participation in international standardization and (ETSI) and R&D (RACE) projects. He is chairman of ETSI SAGE (Security Algorithm Group of Experts) and member of ITAEGV (Information Technology Advisory Experts Group for Information Security).

M. Oskar van Deventer was born in Wageningen, Netherlands in 1965. In 1987 he received the M.Sc. degree in electrical engineering (satellite communication) at the Technical University Eindhoven. Since 1987 he has been working on coherent technology at PTT Research. Since 1991 he is working for the Ph.D. degree, on bi-directional coherent communication and polarization effects in optical networks.

Mr. van Deventer is (co)author of more than 12 papers on optical communication.

Martin K. de Lange was born October 27, 1965. He attended Twente University, and studied computer science from 1984 to 1990.

He is currently a Research Associate at PTT Research Labs, where he works on subjects concerning digital system design, ASIC design, and chip cards.

Oscar J. Koning was born in Amsterdam, Holland on April 27, 1962. He received the M.Sc. degree in physics from the University of Amsterdam in 1988.

In the same year he joined PTT Research as a research staff member, where he worked on coherent communication systems, frequency management, and optical amplifiers.

Jean-Paul Boly studied Discrete Mathematics at the Eindhoven University of Technology, Eindhoven, the Netherlands.

In 1987 he joined the Cryptology group of PTT Research, the research institute of the Dutch PTT. His activities include the design and evaluation of security systems and advanced electronic payment systems, and participation in international R & D projects within the RACE and ESPRIT programs.

Johan P. Bekooij was born in Leiden, The Netherlands, in 1955. He received the M.Sc. degree in physics from the Rijksuniversiteit Leiden, in 1977, and the Ph.D. degree from the Katholieke Universiteit at Nijmegen in 1983. His thesis was on high-resolution microwave and laser spectroscopy on molecular species. As post-doc, he was involved in far-infra-red spectroscopy on ions.

In 1985 he joined PTT Research at the Dr. Neher Laboratories, where he was engaged in research on optical fiber communications with emphasis on design aspects of coherent optical transmission systems for multichannel networks. Presently, he is with PTT Telecom's Business Unit National Networks, where he is involved in development of network access systems based on optical fiber transmission in the local loop.

J. Anita H. W. Berendschot-Aarts was born in Deurne, Netherlands in 1963. In 1988 she received the M.Sc. degree in mathematics at Eindhoven University of Technology.

In the same year she joined PTT Research as a research staff member, where she worked on cryptology. Since 1992 she has been working on the development of cryptographic applications at PTT Contest.

Cyriel P. Spruijt received the M.Sc. degree in electrical engineering from the Twente University in 1988. For military service he worked at TNO/FEL laboratories.

Subsequently, he joined PTT Research and started in the signalling working group. His current activities focus on corporate communication systems.

Kees M. de Blok was born on July 6, 1954. After an electro-technical education he joined PTT Research on 1971. Until 1978 he worked on audio/video transmission, scribophony, digital filters, etc. From 1978 he was involved in the development of measuring and installation methods for the first direct detection optical fiber links in the Netherlands. From 1984 he was involved in the development and realization of coherent optical links.

Maarten F. L. van Nielen was born July 2, 1957. He studied mathematical engineering at the University of Eindhoven (1975-1984). He was a Research Associate with Physical-Electrical Lab's in The Hague from 1985 to 1987. He is currently a Research Associate and project leader at the PTT Research Lab's where he works on subjects concerning network planning, performance and dimensioning. He has published two books on broad-band communication. He has experiences in validation of network concepts with regard to capacity and

economic feasibility (for local loop networks, networks based on coherent detection and MAN and LAN's).

A. Kees van Bochove received his masters degree in physics at the Delft University of Technology in 1976. He has been active in several areas: laser physics and non-linear optics (Delft University of Technology), infrared atmosphere optics (Physics and Electronics Laboratory of the Institute for Applied Research, FEL-TNO), and nano-and picosecond spectroscopy and photosynthesis (University of Leiden). In 1983 he joined Royal PTT Netherlands (PTT Research) and worked mainly on coherent optical communication systems. Since 1991 he is

head of the communication systems department of PTT Research. He has been a member of the Technical Program Committee of a number of international conference on optical communications: IOOC, ECOC, and OFC. He has reviewed a number of projects for the European Committee (ESPRIT program) and for the Foundation of Fundamental Research on Matter (FOM). Since fall 1991, van Bochove is part-time professor at the University of Twente, the Netherlands, teaching optical Network Technology.

Rob F. M. van den Brink graduated in 1984 from the Technical University Delft in the Netherlands, with a degree in electro-technical engineering. His graduation project concerned the development of feeds for microwave antennas.

He joined the same university to work on microwave remote sensing experiments, but changed in 1985 to join PTT Research in the Netherlands. Since then he worked on fiber-optical transmission systems. He developed wide-band optical receivers and transmitters up to a few gigahertz, and various

new measurement and software tools for optoelectronic circuits. His group designed various analog circuits for coherent optical transmission systems, both for internal projects and for the ESPRIT-2054: UCOL project. Currently he is working on his PhD-thesis on a systematic design approach for wide-band analog circuits, applied to high performance optical receivers.