Coherent Optical CDMA (OCDMA) Systems Used for High-Capacity Optical Fiber Networks-System Description, OTDMA Comparison, and OCDMA/WDMA Networking

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***Abstract*—As the wavelength resource in mainstream wavelength-division multiple-access (WDMA) systems becomes exhausted, and the bit-rate limitation within a single wavelength bandwidth is reached, alternative approaches to implementing a high-capacity optical fiber network need to be investigated. Coherent optical code-division multiple-access (OCDMA) systems, that can access many users simultaneously and asynchronously (or synchronously) across the single wavelength and same timeslot via spread spectrum techniques, are one alternative. In the longer term, the advantages of OCDMA in tandem with WDMA (OCDMA/WDMA) networks are compelling and worthy of further investigation in the goal of realising an extensive, flexible, high throughput and easily managed optical telecommunication infrastructure. In this paper, coherent OCDMA systems are introduced, and the issues of the system implementation within high-capacity optical fiber networks are discussed. A performance comparison between OCDMA and OTDMA systems is then carried out, both of them using narrow pulse laser sources. An optical fiber network utilizing coherent OCDMA techniques as one layer of a multiplexing hierarchy, in tandem with WDMA, is illustrated and a possible hybrid OCDMA/WDMA network architecture (and its performances and advantages) is described.**

***Index Terms*—Optical code division multiple access (OCDMA), optical fiber communications and networks, optical time division multiple access (OTDMA), hybrid optical fiber OCDMA/WDMA networks, wavelength division multiple access (WDMA).**

I. INTRODUCTION

AT PRESENT, communications networks based on the synchronous digital hierarchy/synchronous optical network (SDH/SONET) in tandem with asynchronous transfer mode (ATM) switching or internet protocol (IP) routing are in place to satisfy the demand for a range of telecommunication services [1]–[3]. However, the current infrastructure even taking into account further upgrades, will be unable to supply the higher transmission capacity required to support the projected growth in traffic levels, primarily attributed to the exponential use of the Internet together with an increase in the number and range of new services. All-optical fiber networking is considered to be the central solution to overcoming the perceived limitations of a totally electronic evolution. At the core of the development is the huge inherent bandwidth of single mode optical fiber, exhibiting a low-loss spectrum of up to 25 000 GHz [4], [5].

Since the speed at which electrical signal can modulate optical carriers is limited, to fully exploit the optical fiber bandwidth, optical multiplexing techniques have to be deployed. There are three multiplexing alternatives: wavelength division multiple access (WDMA) [6]–[8], optical time division multiple access (OTDMA) [9]–[11] and optical code division multiple access (OCDMA) [12]–[16]. The term "division multiple access" is used throughout, rather than "division multiplexing," to define not simply the transmission multiplex but in addition indicates the access, routing and switching functionality. Whilst WDMA and OTDMA techniques partition the available spectrum and time to different users, respectively, OCDMA techniques multiplex users simultaneously and asynchronously (or synchronously) across the same spectrum and timeslot through a unique code.

The bulk of recent research activity in optical fiber networking has focused on WDMA networks, presently enjoying rapid deployment worldwide as a means of increasing capacity at minimal cost within the existing optical fiber infrastructure. Although WDMA can be used as a degree of design freedom with respect to routing and wavelength selection adding a further dimension to network functionality, the fundamental issue is the limited number of useable wavelengths [17]. This limitation is due to the nonlinearity introduced within the transmission optical fiber that induces crosstalk when transmitting different wavelength signals simultaneously, reducing the flexibility and capacity of the network. Several demonstrations of dense WDMA [8] have been reported recently:

- 34 wavelengths $\times 10$ Gb/s signal transmitted over 8 514 km fiber using an equalization technique via Fourier synthesis of the gain characteristic of the system [18];
- 50 GHz spaced, 32 wavelengths $\times$ 10 Gb/s signal transmitted over 640 km dispersion-shifted fiber with multi-wavelength distributed Raman amplification [19];

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- 25 wavelengths $\times$ 40 Gb/s, 1 Tb/s throughput experiment demonstrated over 342 km in nonzero dispersion fiber [20].

However, upgrading these systems through the introduction of additional wavelengths will become more difficult due to the limitations governed by device characteristics. With respect to channel switching, wavelength routing is the next switching dimension for dense WDMA networks, with interferometric crosstalk being an essential issue in the implementation of cross-connects based on space and wavelength. This kind of crosstalk, increasing with the number of ports and wavelengths, cannot be filtered at the receiver since it predominately occurs at the same wavelength as the signal [21]. Hence, the extent of the wavelength routing that is realisable which in turn determines switch size and flexibility, places fundamental limits on network flexibility [22], [23]. Both practical and fundamental limits will restrict the number of wavelengths, depending on the specific application [24].

Even when considering the partitioning of the huge bandwidth of optical fiber into around 100 sub-bands, additional layers of multiplexing are required to fully exploit each subband (at a bandwidth of approximately 250 GHz). It is clear that currently, due to a more straightforward implementation, WDMA techniques that operate at a small number of wavelengths with each sub-band supporting data rates defined by the modulation and detection speed limitation, is the preferred option. However as the wavelength resource becomes exhausted, a further stage of system upgrade will be required.

Electrical TDMA is utilized to multiplex data from independent WDMA users into single wavelength channels before then transmission across the network [25], [26]. To overcome the bit-rate limitation imposed by electronics within a single wavelength bandwidth, OTDMA techniques using narrow optical pulse laser sources have been developed [9]–[11]. Since the approach uses extremely narrow optical timeslots with correspondingly large bandwidths, a natural increase in the data rates (40 Gb/s–100 Gb/s or higher) at a single wavelength bandwidth, is obtained by multiplexing low bit rate tributary data streams directly in the optical domain. To further increase the capacity, a combination of OTDMA with WDMA have been developed as follows:

- 7 wavelengths $\times$ 200 Gb/s (1.4 Tb/s) transmitted through 50 km of dispersion shifted fiber [27];
- 25 wavelengths $\times$ 40 Gb/s (1 Tb/s) transmitted over 342 km [28];
- 19 wavelengths $\times$ 160 Gb/s (3 Tb/s) transmitted over 40 km of dispersion shifted fiber using supercontinuum WDMA sources [29].

However, the technology involved in the implementation of OTDMA is very different from that of WDMA; whereas the latter systems use components that are available commercially, most of the devices required to implement OTDMA are still confined to the laboratory. In addition, OTDMA has still a number of difficult hurdles to solve such as synchronization and the immature technology of selecting one channel out of multiplexed picosecond optical pulse data streams. Hence, scope for evolving new innovative methods exists in order to determine the best trade-off regarding capacity, performance, flexibility and complexity of a variety of approaches to network provision.

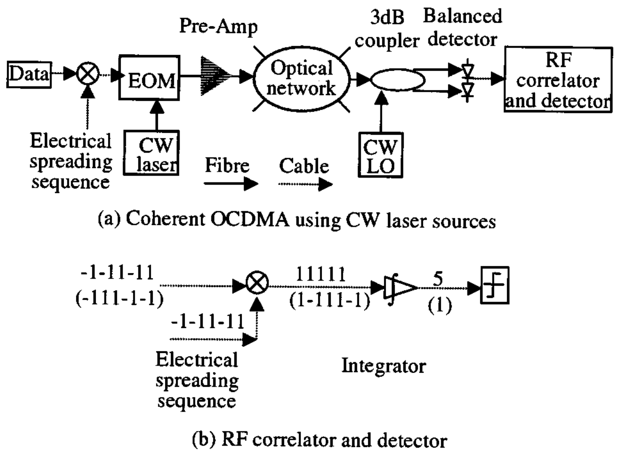
An alternative to providing additional multiplexing at a single wavelength is through CDMA techniques. Direct-sequence (DS) CDMA is a technique originating from spread spectrum (SS) communications [30]. DS-CDMA techniques play an important role in current wireless communication systems such as cellular [31], microcellular [32], indoor [33] and satellite communications [34]. Efficient multiple access capacity, effective reuse of the frequency resource, asynchronous access capacity and immunity to the multipath fading characteristic of wireless transmission are important characteristics driving the use of this approach. DS-CDMA is also the likeliest candidate for the next generation of broad-band mobile communications [35].

CDMA techniques can be implemented directly in the optical domain based on continuous-wave (CW) [12], [13] or ultrashort optical pulse laser sources [14]–[16]. Coherent OCDMA techniques governed by similar principals to radio DS-CDMA, can multiplex multiple users onto the huge optical spectrum via spread spectrum techniques, offering the same transmission capacity as OTDMA systems (via interference cancellation in an asynchronous transmission mode [36]). The techniques can be used as an additional optical layer of a multiplexing hierarchy based on WDMA and allow electrical user signals access to the optical network in a more natural way [37], [38]. The asynchronous operation of OCDMA systems is a very desirable characteristic of any multiplexing technique especially at high data rates, and the accurate time of arrival measurement capability relaxes the problem of synchronization inherent in OTDMA implementations [39], [40]. OTDMA and OCDMA systems both utilize narrow pulsed laser sources, but the latter has the advantage of de/multiplexing and detection relying on commercial components rather than new generation devices required by OTDMA [9]–[11], [16]. Hence, the attraction of the approach is compelling despite the added implementation complexity brought about at the receiver due to need for carrier phase locking and the phase stability requirements (the linewidth) of the laser sources [41]. A network employing OCDMA/WDMA is capable of establishing more traffic connections than a network using WDMA only. These results also suggest that OCDMA/WDMA reduces connection setup failure in any network condition and hence, reduces connection setup time as well as node buffering requirements [42]. In the longer term, OCDMA in tandem with WDMA is thus worthy of further investigation in the goal of realising an extensive, high capacity and easily managed optical telecommunication infrastructure.

In the following sections, coherent OCDMA systems are introduced. A performance comparison between OCDMA-OTDMA is then carried out. An optical fiber network utilising the OCDMA technique as one layer of the multiplexing hierarchy, in tandem with WDMA, is developed, and a possible hybrid OCDMA/WDMA network architecture (and its performances and advantages) is described.

II. OCDMA System Description

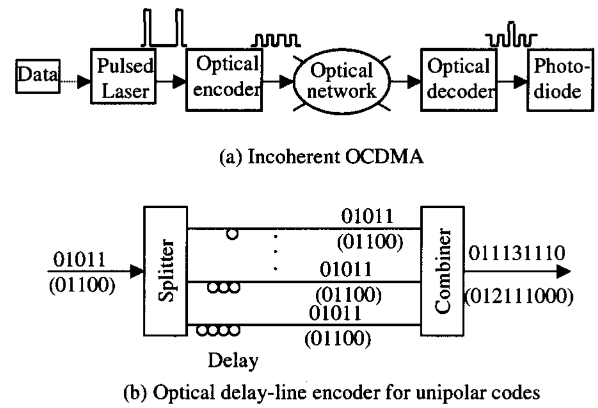
In the optical domain, CDMA implementations can use both CW and narrow pulse laser sources. In this section, OCDMA



(a) Coherent OCDMA using CW laser sources

(b) RF correlator and detector

Fig. 1. Coherent OCDMA systems using CW laser sources with full coherent detection.



(a) Incoherent OCDMA

(b) Optical delay-line encoder for unipolar codes

Fig. 2. Incoherent OCDMA systems using pulsed laser sources with passive matched filter detection.

systems with particular application in high-capacity hybrid OCDMA/WDMA network implementations are illustrated and the key application issues are investigated.

A. Generalized System

1) OCDMA Using CW Laser Sources: OCDMA system using CW laser sources (Fig. 1), similar to radio DS CDMA principals, can be based on coherent implementation [12], [13]. As shown in Fig. 1(a), the data bits at the transmitter are spread by high-speed electrical bipolar $(+1, -1)$ sequences that then modulate a CW laser source via an electrooptic modulator (EOM) for transmission. The transmitted optical signals for different users are multiplexed on one channel of an optical fiber network through the assignment of unique codes.

At the receiver, the received optical signal beats with a CW local oscillator via a 3-dB coupler and a dual balanced detector, effectively performing the function of a mixer. The laser frequency of the CW local oscillator is locked to the laser of the transmitter via an external absolute reference. The electrical output signal from the dual balanced detector then undergoes a radio frequency (RF) correlation and detection process [Fig. 1(b)]. The signal is correlated with the electrical code sequence of the desired user, integrated and discriminated to recover the data bit.

An example of the correlation detection process is given in Fig. 1(b) in which the desired code and the nondesired (interference) code are (-1-11-11) and (-111-1-1), respectively. The incoming codes are correlated to the local code (-1-11-11), chip by chip, through a multiplier, and the resulting correlation sequence is (11111) for the desired signal and (1-111-1) for the interference signal. Both are integrated, producing an autocorrelation peak 5 and a cross-correlation interference of 1, respectively. The integrator output is then used to recover the data bit via an estimation process. Since CDMA systems have to support many users, the codes used should satisfy specific correlation conditions: both the time-shifted autocorrelation function of each code and the cross-correlation function between codes must be low when compared to the autocorrelation peak value.

2) OCDMA Using Narrow Pulse Laser Sources: Both incoherent and coherent OCDMA systems using narrow pulse laser sources have been proposed, and most of the research activity has centred on incoherent implementations, driving initially the development of unipolar pseudo-orthogonal (0, 1) codes [14], [15]. For the purposes of comparison, both incoherent and coherent implementations are introduced.

3) Incoherent Implementation: The procedure for an approach using unipolar codes and incoherent passive matched-filtered detection (MFD) directly in the optical domain is shown in Fig. 2(a) [14]. Differing from radio DS CDMA principles, the system relies on a simple, intensity based, pulse time addressing process. A pulse laser source is intensity-modulated by electrical (0, 1) data bits and encoded by an optical delay-line encoder [see Fig. 2(b)] to produce an unipolar signature code.

At the receiver, an optical MFD (an optical delay-line decoder matched to the encoder at the transmitter) produces a peak in the correlation output for the intended user. Data bits are discriminated in the chip duration using a photodiode followed by a thresholding process. An example that illustrates the correlation process is given in Fig. 2(b) in which the desired code (01011) and the nondesired code (01100) are split to the different branches of the optical decoder matched to the desired code. On the branches the signals go through different delay lines, and are then re-combined. At the output of the optical decoder the desired correlation and the interference signals are (011131110) and (012111000), respectively. The following detection process has to determine an autocorrelation peak of 3 in the presence of an interference chip of level 1 and other side-lobe interference.

Compared to conventional electronic bipolar $(-1, +1)$ codes such as Gold codes [43], the cross-correlation function of unipolar codes is high and the number of codes in the family is very low. Thus, long, sparse codes comprising very few ones and narrow pulses have to be employed to support a large number of users and higher transmission capacities, respectively. The implementation is thus limited by the losses of the complex hardware and the requirement for chip duration detection, preventing the use of ultrashort pulses.

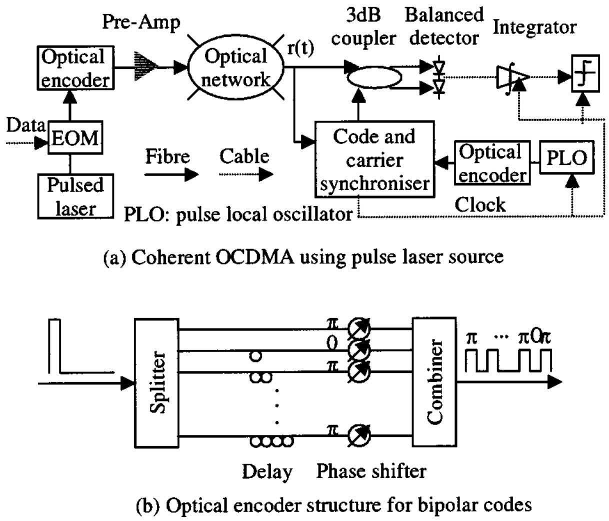


Fig. 3. Coherent OCDMA systems using pulse laser sources with full coherent detection.

4) Coherent Implementation: Coherent OCDMA systems using narrow optical pulse lasers adopt a similar principal as radio DS CDMA [Fig. 3(a)] [16]. A pulsed laser emits a narrow optical pulse sequence at an interval of the data bit duration. The sequence is then phase-modulated by electrical data bits via an EOM and encoded by an optical tapped delay line encoder with different delays and predetermined phase shifts on each branch, producing an optical bipolar code [Fig. 3(b)].

At the receiver, a pulsed LO in tandem with the same optical encoder as that of the user transmitter is used to generate the code of the intended user. Through proper synchronization of the code [39], [40] and optical carrier phase [41], the local code is multiplied by the received signal, chip by chip via a 3 dB coupler followed by a balanced detector (optic-electromultiplier). The correlation process is similar to that introduced in Fig. 1(b). The output of the balanced detector is an electrical signal, comprising the autocorrelation and cross-correlation components, subsequently integrated over a bit duration and discriminated to recover the data bit.

The issues pertinent to the implementation of the coherent OCDMA systems within high-capacity optical networks are discussed in the following subsections.

B. Near-Far Issue

The "near-far" problem is an essential issue in most CDMA systems, especially in wireless applications. Fortunately, the transceivers in an optical fiber networks are fixed, and to a certain extent, the optical path loss between the transmitter and the receiver can be predicted. Hence, a gain-clamped preamplifier [Figs. 1(a) and 3(a)] can be used to compensate for optical power loss, so that all the transmitted optical signals originating from different locations can be received at similar optical power levels.

C. Code Synchronization

Code synchronization is of major importance for efficient operation of any CDMA system. It is even more crucial in coherent OCDMA systems using full coherent detection since synchronism has to be maintained between the incoming and the local codes. Code synchronization can be realized through a two-stage process: a coarse alignment referred to as code acquisition [39] and a subsequent fine alignment referred to as code tracking [40].

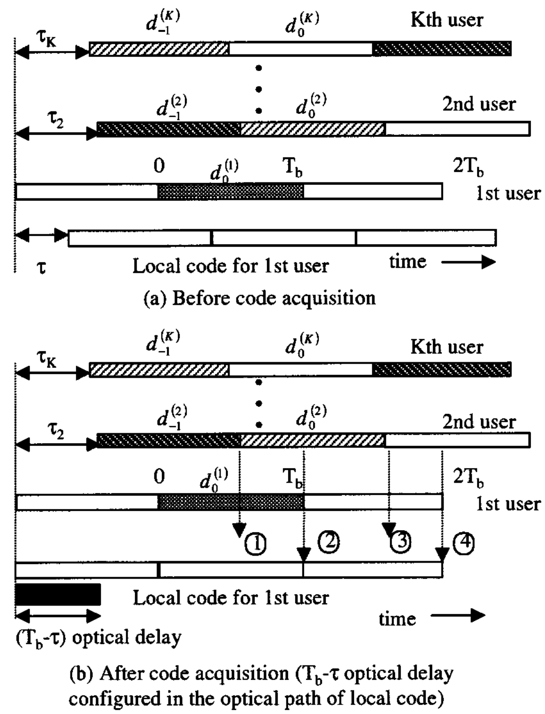


Fig. 4. Data streams in asynchronous CDMA users.

1) Code Acquisition: As shown in Fig. 4(a), the difference in time between the desired code (first user) and the local code τ is smaller than one data bit duration T_b. The code acquisition technique relies on a variable optical delay device configured in the optical path of the local code, before the correlation process. Before transmitting data, a training sequence (unmodulated code sequence) is sent to the receiver to aid in the coarse acquisition of the incoming code to within a fraction (usually one-half or one-fourth) of the chip duration. The acquisition process is progressed through the adjustment of the optical delay, taking correlations between the two codes sequentially until the code phase difference is compensated by the optical delay [Fig. 4(b)], thereby locating the peak of the autocorrelation function.

The performance of a noncoherent code acquisition process in the presence of multiuser interference and optical device noise has been investigated in [39]. The acquisition is performed in a noncoherent manner, the simple reason being that the optical carrier phase is still unknown. Once the codes are acquired, the process is stopped and the system moves to transmitting data.

2) Code Tracking: The receiver configuration for full coherent OCDMA detection [the same concept can be used for the system in Fig. 1(a)] is depicted in Fig. 5. The receiver executes three processes: a noncoherent delay-locked code process, a decision-directed phase locking process and a demodulation

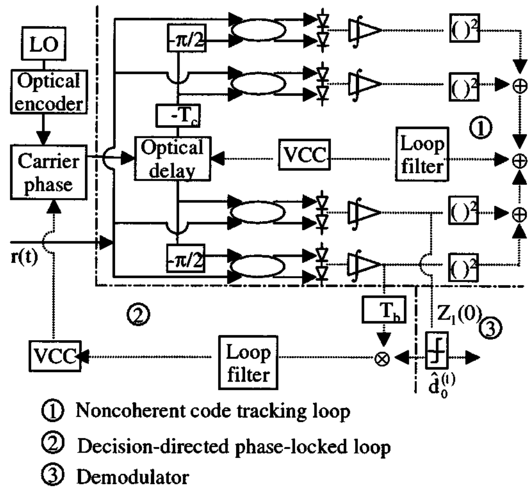


Fig. 5. Receiver configuration with full coherent reception for use in coherent OCDMA systems.

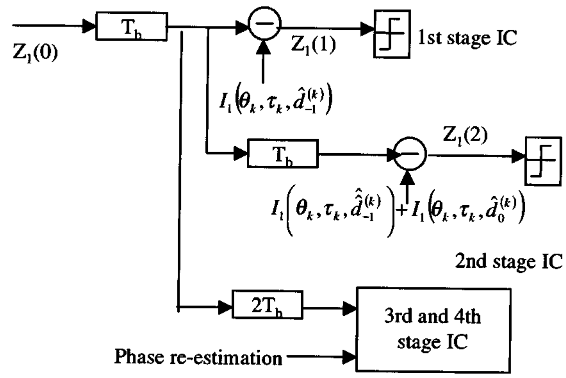


Fig. 6. Multistage interference cancellation (IC) for coherent OCDMA systems.

process. The key to simplifying the configuration is to effectively combine the phase locked loop and the demodulator with the code-tracking loop.

Code tracking maintains the incoming and local codes in synchronism for the duration of the transmission. Noncoherent operation is also used for the code tracking because, at low signal-to-noise ratios (SNR's), it is difficult to lock the optical carrier phase prior to code tracking. Noncoherent code tracking thus offers an important advantage since the tracking performance is not directly influenced by the carrier phase locking process.

In the tracking process, the local code and its one code chip duration T_c delayed version of the in-phase and the quadrature-phase components are generated by a T_c optical code phase delay device and $\pi/2$ optical carrier phase shifter. The local signals are correlated with the received optical signal by a 3-dB coupler and a dual balanced detector. The resultant correlation output is used to drive a loop filter and voltage controlled clock (VCC). Since the transceivers within OCDMA systems are fixed, the code delay of all users is arbitrary but constant within the duration of the transmission. Furthermore, the code tracking performance can be improved by increasing the optical power and reducing the loop bandwidth [40].

D. Carrier Phase Synchronization

Carrier phase synchronization is a prerequisite for successful demodulation. The phase locking process (Fig. 5) is based on a digital decision-directed loop. In this loop, the data recovered by the demodulator is used to multiply a one-bit delayed output of the integrator, subsequently of use for the phase locking operation, removing the information data component. The discriminator output is then fed into a loop filter, followed by a VCC, used to drive a continuously variable optical carrier phase modulator in order to align the carrier phase. The factors limiting the performance of the phase locking are multiuser interference, phase noise and optical shot noise [41]. The required locking performance has to be obtained through selection of a pulsed laser source with specified linewidth. The required laser linewidth to bit-rate ratio is about 10^{-4} at a phase locking error variance of 0.03 and about 10^{-5} at 0.01 [41].

E. Polarization Control

Polarization control is necessary in coherent systems to align the polarization between the received and local optical signals. Fine polarization control ensures and maintains the maximum photocurrent produced by the correlation. In the extreme case, no photocurrent is produced at the output of the balanced detector if the polarization directions of the two signals are orthogonal. Alignment of the polarization may be realized based on polarization control techniques such as installing special polarization-maintaining fibers, polarization tracking, polarization scrambling, polarization shift keying and polarization diversity [44]. Many demonstrations of coherent optical communication systems have managed the issue of polarization [45], [46].

F. Multiuser Interference

Although the coherent OCDMA systems in Figs. 1(a) and 3(a) using bipolar orthogonal Walsh codes [16] in synchronous transmission have no cochannel interference. Multiuser interference is a major issue causing severe performance degradation in asynchronous transmission due to the nonorthogonal properties of the spreading codes. Whilst the poor bit error rate (BER) (10^{-2}–10^{-3}) of current radio DS-CDMA systems is acceptable for voice transmission in current wireless communications [31], this BER performance is unacceptable in an optical fiber network (where a generally accepted BER is in excess of 10^{-9}). However, this fundamental interference is not completely random and is a function of carrier phase, access delay and data bits of nondesired users. If the random ingredients of all users are estimated by the use of multiuser and multistage detection, multiuser interference can be rebuilt and removed from the desired signal [47], [48].

The interference cancellation approach proposed for coherent OCDMA systems of Fig. 3(a) is shown in Fig. 6 [the principal is also suitable for the system in Fig. 1(a)]. Since full coherent reception is used, the carrier phase and the code access delay can be derived from the code tracking and carrier phase locking processes. Data symbols are known from the pre-stage detection. The interference can be rebuilt via the estimated ingredients and removed from the desired threshold decision signal.

The threshold decision is then repeated. The key advantage derived from the proposed system implementation, is that the cancellation processes can be performed in the electrical domain.

It is assumed that the first user is desired by the receiver, and the other users $(k = 2, \ldots, K)$ are nondesired users. In Fig. 6, the signal from integrator prior to the threshold decision for the first user can be represented as

$$Z_1(0) = AT_b d_0^{(1)} + I\left(\theta_k, \tau_k, d_{-1}^{(k)}\right) + I\left(\theta_k, \tau_k, d_0^{(k)}\right) + N_1 \quad (1)$$

where "0" indicates decisions without multiuser interference cancellation. $d_0^{(1)}$ is the data bit of the first user [Fig. 4(b)]. T_b is the data bit duration, related to the code chip duration as $T_b = NT_c$ where N is the code period. A is the optical-electro conversion factor, and N_1 is the optical shot noise. The second and third terms in (1) are multiuser interference, represented by

$$I\left(\theta_k, \tau_k, d_{-1}^{(k)}\right) = A\sum_{k=2}^{K} \cos\theta_k d_{-1}^{(k)} R_{k,1}(\tau_k) \quad (2a)$$

$$I\left(\theta_k, \tau_k, d_0^{(k)}\right) = A\sum_{k=2}^{K} \cos\theta_k d_0^{(k)} \hat{R}_{k,1}(\tau_k) \quad (2b)$$

where $R_{k,1}(\tau_k)$ and $\hat{R}_{k,1}(\tau_k)$ are the continuous time partial cross-correlation functions defined in [49]. θ_k is the carrier phase, τ_k is the access delay and $d_i^{(k)}$ $(i = -1, 0)$ are data symbols [illustrated in Fig. 4(b)].

1) First-Stage Cancellation: It can be seen from (1) that the desired data bit $d_0^{(1)}$ is interfered by two bits ($d_{-1}^{(k)}$ and $d_0^{(k)}$) from the users $(k = 2, \ldots, K)$ in the channel. As illustrated in Fig. 4(b), $d_{-1}^{(2)}$ is estimated at point 1 as $\hat{d}_{-1}^{(2)}$ at the receiver for the second user; the code timing τ_2 and the carrier phase θ_2 are known from the code tracking and carrier phase locking, respectively. Hence, the interference due to $d_{-1}^{(2)}$ with duration τ_2 can be removed from the decision making process of user one. A similar process is applied to all other nondesired users at point 2 where the first stage cancellation is carried out. The threshold decision signal for the first stage cancellation is

$$Z_1(1) = Z_1(0) - I\left(\theta_k, \tau_k, \hat{d}_{-1}^{(k)}\right) \quad (3)$$

where "1" represents the threshold decision of the first stage cancellation, and the estimated interference is

$$I\left(\theta_k, \tau_k, \hat{d}_{-1}^{(k)}\right) = A\sum_{k=2}^{K} \cos\theta_k \hat{d}_{-1}^{(k)} R_{k,1}(\tau_k). \quad (4)$$

2) Second-Stage Cancellation: In the second-stage cancellation, after a waiting period of T_b, the data symbols, $\{d_0^{(k)}\}$, have been detected as $\hat{d}_0^{(k)}$ for all users $(k \neq 1)$. Since all transmitted data experience similar processes, at point 4 the users will have already obtained second-stage estimates for data bits $\{d_{-1}^{(k)}\}$ as $\{\hat{\hat{d}}_{-1}^{(k)}\}$ using the first-stage cancellation [Fig. 4(b)].

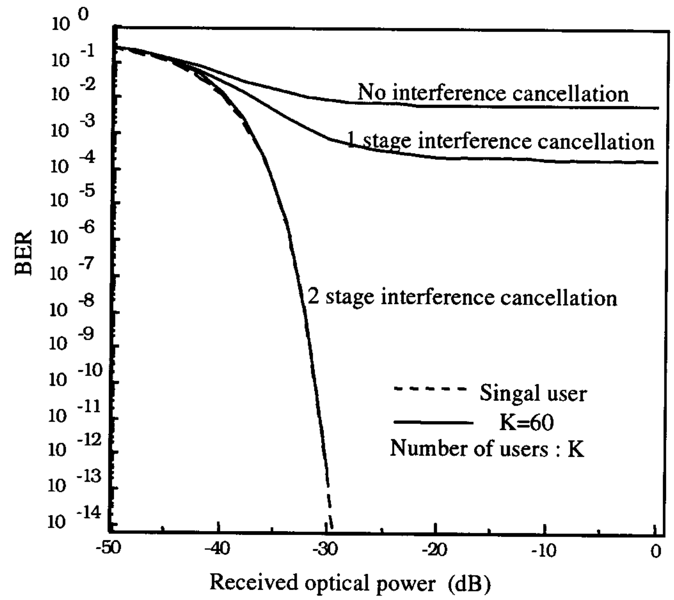


Fig. 7. BER as a function of received optical power with interference cancellation.

Using $\hat{\hat{d}}_{-1}^{(k)}$ and $\hat{d}_0^{(k)}$, the threshold decision signal for the second stage cancellation is now given by

$$Z_1(2) = Z_1(0) - I\left(\theta_k, \tau_k, \hat{\hat{d}}_{-1}^{(k)}\right) - I\left(\theta_k, \tau_k, \hat{d}_0^{(k)}\right) \quad (5)$$

where

$$I\left(\theta_k, \tau_k, \hat{\hat{d}}_{-1}^{(k)}\right) = A\sum_{k=2}^{K} \cos\theta_k \hat{\hat{d}}_{-1}^{(k)} R_{k,1}(\tau_k) \quad (6a)$$

$$I\left(\theta_k, \tau_k, \hat{d}_0^{(k)}\right) = A\sum_{k=2}^{K} \cos\theta_k \hat{d}_0^{(k)} \hat{R}_{k,1}(\tau_k). \quad (6b)$$

Fig. 7 illustrates the BER as a function of the received optical power for 60 users where two-stage interference cancellation has been employed [36]. One stage cancellation partly cancels multiuser interference; significantly improved system performance is obtained through the two-stage cancellation. It is clear that two-stage cancellation is very powerful with almost all of the multiuser interference cancelled, achieving the performance equivalent to that of a single user.

Since carrier phase synchronization is also influenced by multiuser interference, using the outputs from the two-stage cancellation process, the carrier phase can be reestimated. Using the reestimated carrier phase information, third and fourth stage cancellation can be performed (Fig. 6), a direct repeat of the first and second stage cancellation, respectively. The results of system performance and the requirements placed on the laser linewidth are given in Table I. The variance of the phase estimation (σ_ε^2) and the number of simultaneous users (K) at an error probability of 10^{-9} and received optical power of -30 dBm for different code length are given. By generating phase reestimation through interference cancellation, the

TABLE I
VARIANCE OF PHASE ERROR AND NUMBER OF USERS AT BER $= 10^{-9}$ AT A RECEIVED POWER OF -30 DBM

Code length: N	Without IC in PE				With IC in PE			
	$\Delta\gamma/R_b$=5.0e-4		$\Delta\gamma/R_b$=1.0e-4		$\Delta\gamma/R_b$=1.0e-2		$\Delta\gamma/R_b$=3.0e-3	
	σ_ε^2	K	σ_ε^2	K	σ_ε^2	K	σ_ε^2	K
31	0.050	19	0.028	31	0.050	16	0.025	31
63	0.050	38	0.029	63	0.052	33	0.025	63
127	0.050	77	0.029	127	0.053	67	0.025	127

IC: Interference cancellation, PE: Phase estimation

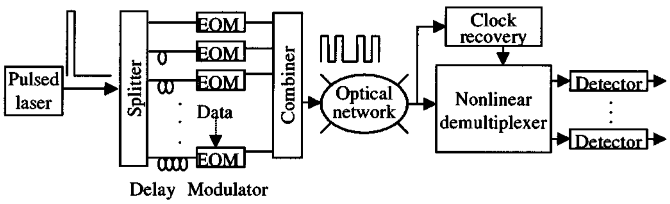


Fig. 8. Schematic of a general OTDMA systems using optical pulse laser sources.

requirement on the laser linewidth to bit rate ratio $(\Delta\gamma/R_b)$ can be reduced from 10^{-4} to 3×10^{-3}.

III. SYSTEM COMPARISON: OTDMA VERSUS OCDMA

OTDMA utilising narrow optical pulse laser sources is a well-documented method of multiplexing for very high rate transmission (40–100 Gb/s or higher) at a single wavelength. Since many approaches to implementing an OTDMA system can be found in the literature together with experimental proof-of-principle demonstrations [9]–[11], [50]–[54], Fig. 8 simply shows the basic principles of operation. A pulsed laser is used to produce a regular train of narrow optical pulses (pulse width considered to be the same as the timeslot) at a repetition rate that corresponds to the bit rate of the (electrical) data signals. The optical pulse train is split into several separate paths, and each of them is individually modulated by an electrical data channel, delayed by a fraction of optical delay (equivalent to the timeslot), and combined to form a single multiplexed optical data stream. At the receiver, the optical data stream is demultiplexed, then detected to recover the information. Both electrooptic [50] and all-optical gating [51], [52] demultiplexing methods have been demonstrated. Some means of clock recovery at the bit rate is required to drive and synchronise all demultiplexers [53], [54].

A comparison between OCDMA and OTDMA, from the system implementation viewpoint with particular regard to technology issues, is summarized in Table II and discussed.

Laser Sources: Both OCDMA and OTDMA systems employ narrow optical pulsed laser sources. To enable multiplexing with low crosstalk between adjacent channels, the duration of the optical pulse must be significantly less than the duration of the allowed timeslot or chip duration. In addition, the pulses have to be as spectrally pure as possible so that pulse broadening problems due to the interaction of source characteristics with fiber chromatic dispersion are minimized [10]. Another very important issue with laser sources is the jitter on the output pulses, which should be minimized for successful recovery of the data. Low jitter permits narrow time separations between adjacent timeslots or chips. Since OCDMA systems employ full coherent reception, narrow laser linewidths and high carrier phase stability is also required.

Multiplexing: As depicted schematically in Figs. 3(b) and 8, OTDMA multiplexers are simpler than OCDMA encoder geometries. The added complexity of the encoder in OCDMA results in an increased optical power loss, since relatively long spreading codes ($>$10 chips) may be required in extensive asynchronous OCDMA implementations. However, the issue will not be a major obstacle to implementation given the strides made in component development, especially in opto-hybrid integrated circuits featuring a combination of passive and active devices. The signals are multiplexed by an interferometer-type multiplexer realized in a planar lightwave circuit geometry [52].

Transmission and Dispersion: In both OCDMA and OTDMA signal transmission, optical amplification is used routinely to compensate for component insertion losses, avoiding SNR degradation and maintaining acceptable BER's. Chromatic dispersion is another major issue, and techniques such as dispersion compensation [55], spectral inversion and dispersion management [56], [57] are required to reduce its effects on transmission performance. For step-index fiber, dispersion compensation techniques using opposite dispersion optical fiber at the transmitter have been used to provide unrepeatered transmission. For dispersion shifted fiber systems, nonlinear transmission (solitons) can be used over a wide wavelength range or minimization of the dispersion can be achieved by operating near the dispersion zero. OCDMA is robust to crosstalk from adjacent chips because the crosstalk is asynchronous to the intended chips, and can be rejected by the despreading process. In contrast, the crosstalk from an adjacent timeslot in OTDMA directly influences the decision making process. Since CDMA channel signals are completely random, i.e., no "distinct" pulses can be observed in the channel, OCDMA techniques are more resistant to crosstalk from adjacent chips and are thus more robust to dispersion than OTDMA.

Synchronization and Clock Recovery: Both OCDMA and OTDMA demultiplexers are driven at the electrical data clock rate and not at the code chip or full optical timeslot data rates. Hence, both require an accurate electrical clock at the transmitter and receiver. The ability to extract clock signals from OTDMA data is vital to a successful demultiplexing process. Either phase locked loops (electro-optic or optical) [53], [58], [59] or all-optical mode-locking [54] clock recovery techniques have been demonstrated. All optical clock recovery techniques utilize a component nonlinearity either in optical fiber and semiconductor laser amplifiers for their operation. In comparison, time synchronization in OCDMA systems is much simpler, as described in the previous section. However, fine carrier phase synchronization is required to lock the carrier phase of the incoming signal to the local code.

Demultiplexing: Both electro-optic [50] and all-optical [51], [52] nonlinear or gating demultiplexing methods have been demonstrated in OTDMA systems, most of the devices required

TABLE II
COMPARISON OF OCDMA AND OTDMA TECHNIQUES USING NARROW OPTICAL PULSE SOURCES

	Laser Sources	Multiplexing	Transmission and Dispersion	Synchronization and Clock Recovery	Demultiplexing
OCDMA	• *coherent laser sources* • *phase stability* • small time-bandwidth product	• **asynchronous** • *complexity of encoder* • *large power loss*	• **more resistant to crosstalk from adjacent chips** • **more robust to dispersion**	• **easy code phase synchronization** • *complexity of carrier phase* • accurate electrical clock	• **simplicity of devices and process** • **same capacity as OTDMA by the use of interference cancellation**
OTDMA	• small time-bandwidth product	• **simplicity of multiplexing**	• dispersion compensation • dispersion shifted fiber	• *difficulty of time synchronization* • accurate electrical clock	• **large capacity** • *complexity of device and process*

Bold: advantage, *italic: drawback*, underline: key point

however are still confined to the laboratory. The complexity of the demultiplexing process in OTDMA, and the relative immaturity of the hardware required for its implementation, coupled with the difficulties of clock recovery and maintaining synchronization between nodes at ultra high bit rates, is a major obstacle. In contrast, notwithstanding carrier phase synchronization and the concomitant requirement with respect to the laser linewidth, OCDMA receivers rely on a well-understood process using commercially available, mature components. The simplicity of the demultiplexing, given practically realisable code phase synchronization, is one of the major advantages of OCDMA. With the use of the interference cancellation, the OCDMA system matches the transmission capacity of OTDMA.

Integration with WDMA: To increase transmission capacity, OTDMA can be combined with WDMA. Several systems combining the OTDMA with WDMA have been developed, such as reported in [27]–[29]. The componentry derived form the above developments can be harnessed to develop OCDMA/WDMA approaches to system realization.

IV. OCDMA/WDMA BASED OPTICAL FIBRE NETWORKS

WDMA is a simple, natural approach to harnessing the bandwidth of optical fibers. However with ever-increasing demand to support higher levels of traffic, a pure WDMA stance to providing network capacity and functionality will not be sufficient, fundamentally limited by the number of useable wavelengths. Therefore another layer of multiplexing is required for future network expansion; OCDMA and OTDMA are both candidates as additional multiplexing strategies on each WDMA subband. Here coherent OCDMA approaches are developed taking into consideration the implementation arguments presented in the previous sections.

A. Partition of Optical Bandwidth

Implementing OCDMA in large networks has posed a difficult challenge for network designers. This is because OCDMA by itself is a broadcast technology, with all information going to all parts of the network, most suitable for local area networks.

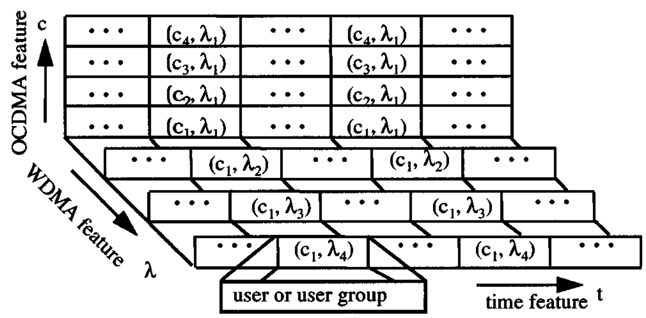


Fig. 9. Wavelength and code allocation within optical fiber networks based on OCDMA/WDMA.

However, through integration with WDMA, the application sector for OCDMA can potentially extend to the transport layer of the telecommunication hierarchy. The partition of the available optical bandwidth for the use within a hybrid OCDMA/WDMA network is illustrated in Fig. 9. The total spectrum is split into a number of the subbands, and each of the subbands is further utilized as optical spread spectrum. Low bit rate users or user grouptraffic are assigned codes and thus multiplexed onto the subbands.

B. Integrating OCDMA and WDMA

There are a number of ways to implement an OCDMA/WDMA network. A simple example is shown in Fig. 10. To develop a flexible OCDMA/WDMA network, the entire network area is divided into several subzones, deploying a subnetwork (subnet) in each subzone. It is a three-layered network, consisting of a number of subnetworks interconnected by access nodes. Each of the access nodes also serves as a gateway for the user and transport tiers. Traffic from the user subnet nodes is offered into the transport network via the access nodes. As the traffic routed along the optical path from access node A to access node C and via access node B increases, the capacity across the optical path will then have to increase. In a pure WDMA network implementation, adding more wavelength channels within each fiber normally accommodates traffic growth. However, in the

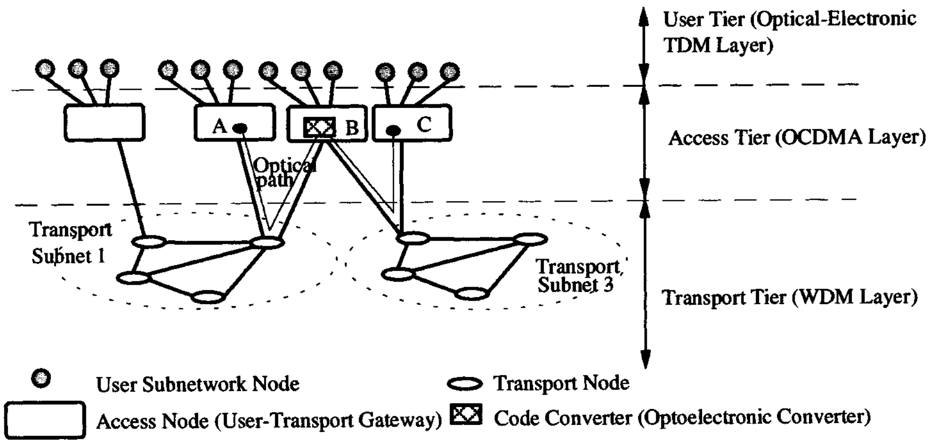


Fig. 10. A Simplified three layered network.

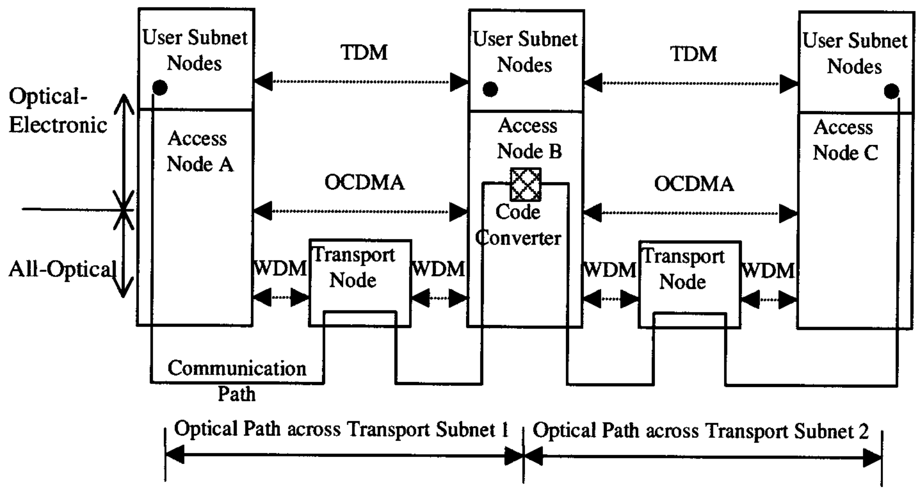


Fig. 11. OCDMA/WDMA network operating strategy.

proposed OCDMA/WDMA network, this can be achieved by introducing coded channels at each wavelength.

Fig. 11 shows the various stages experienced by the traffic routed from access node A to access node C. Traffic from the user subnet is first multiplexed onto a coded channel or a set of coded channels. It is then routed to the transport node adjacent to the access node. At the transport node, the traffic is multiplexed onto an appropriate wavelength according to its destination. At each intermediate transport node, traffic is routed to the appropriate output port according to its wavelength. The traffic may undergo wavelength conversion, performed directly in the optical domain using optical wavelength converters. A generic transport node architecture is shown in Fig. 12.

C. The Management Hierarchy

Fig. 13 shows the overall management hierarchy for an OCDMA/WDMA network. The physical layer transmits bits over a communication channel. It deals with the optical interfaces over the physical medium and also provides network security functions such as network failure protection.

The WDMA layer builds on the transmission capability of the physical layer. It provides the services to the OCDMA layer and all the photonic provisioning and restoration functions within the network. Traffic entering the WDMA layer is multiplexed onto the appropriate wavelengths. Traffic is routed across the network according to its wavelength and not its header address. Hence, it provides a course routing function. It also provides an optical path protection and configuration function by reconfiguring and rerouting the wavelength channels. All traffic carried by the affected channels will be reconfigured or rerouted according to the new optical configurations and routes defined by wavelength.

The OCDMA layer builds on the optical topology provided by the WDMA layer. It provides codes for each individual traffic stream offered by the user subnet layer. Effectively the function of the OCDMA layer is to increase the capacity offered within the wavelength channels. Each traffic stream can be multiplexed into a single or a set of coded channels at each wavelength. This allows multiple class traffic types to be carried within a single wavelength channel. Hence, the OCDMA layer provides all the necessary management and operating functions for each coded channel and indirectly for each traffic stream. These include routing of each traffic stream from one user subnet to another user subnet across the

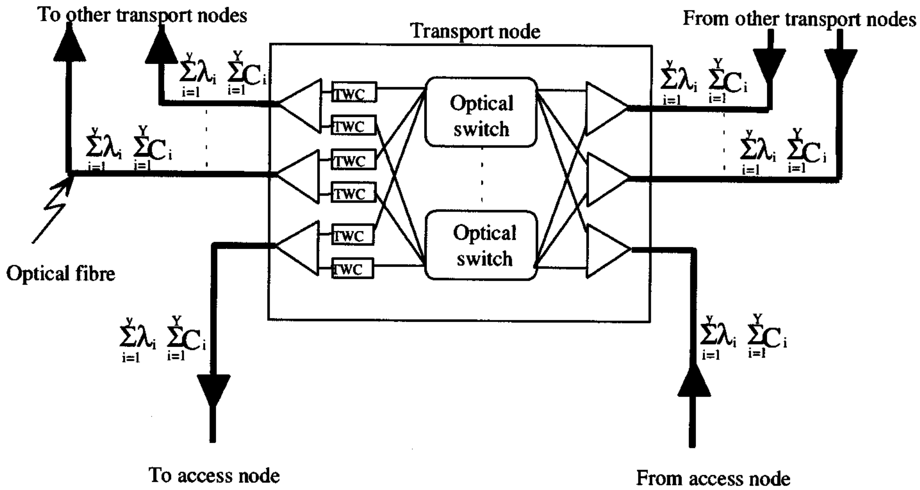


Fig. 12. Schematic architecture of the transport node.

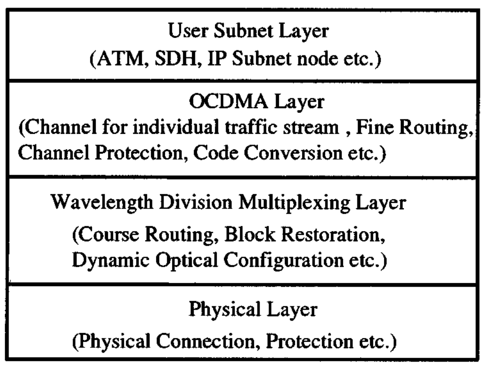


Fig. 13. General network management functions.

hybrid network, restoring failed traffic connection by assigning alternative coded channels or a set of coded channels and resolving the channels contention using code converters. The user subnet layer manages the way the traffic is formatted or presented such as SDH, ATM, or Internet protocol (IP). It provides the monitoring and control functions on traffic offered into the transport tier.

In the network example shown in Fig. 10, each transport node does not have a direct add-drop capability. In order to introduce this capability, an access node functionality is added into each of the transport layers. This reduces the network layers to two: the user and the transport tiers. Hence, traffic from the user tier can be directly offered into the transport tier as shown in Fig. 14. The schematic architecture of the transport node is shown in Fig. 15.

D. Connection Protocol

Assume that each user subnet node is allocated a set of distinct codes. In the network shown in Fig. 10 connections can established using the existing network wavelength assignment and connection protocols [60], [61]. For example, whenever a user subnet node wishes to communicate with other user subnet nodes, it sends a request message (REQ) to the access node. The access node will then evaluate the suitable path to establish the connection based on the information it receives about the network condition. It will evaluate the shortest path given the free wavelength channel status. This information about the node condition is shared among the transport nodes within the same transport subnet and is regularly updated. Once the path has been identified, the access node will reserve the wavelength channel at the selected output fiber of the access node. The access node will then forward the REQ to the transport node connected to the output fiber. This intermediate transport node will then decide whether to forward the REQ message to the next intermediate transport node. If no wavelength channels along the selected path are free, then the REQ message will be removed and a failure acknowledgment (NACK) message is sent back to the user subnet node. If there is a free wavelength channel then that wavelength is reserved and the REQ will be forwarded to the next intermediate transport node. The procedure is repeated at each intermediate node until it reaches the access node connected to the destination subnet.

If the destination user subnet node is connected to a different transport subnet, then the access node connected to the source user subnet will try to establish connection to the access node connecting the destination transport subnet. That access node to the destination user subnet node then uses the same REQ message in order to establish connection within the transport subnet. Whenever a connection is successfully reserved, than the access node connecting the destination user subnet will send an acknowledgment back to the access node connecting the source user subnet. Once the source user subnet node receives the ACK message, it will release the traffic into the transport network.

The network shown in Fig. 14 however requires different connection protocols. Unlike the protocols described above, each code channel can hop onto a wavelength channel occupied by some other connections. This is because of the add–drop capability introduced within each transport node. The transport node connecting the source user subnet node will first seek suitable paths with high probability that one of the wavelengths within the fiber along the path is not occupied by traffic using the same codes. Once identified, the access node will reserve the codes within the wavelength channel at the selected output port and forward the REQ to the intermediate transport node. The

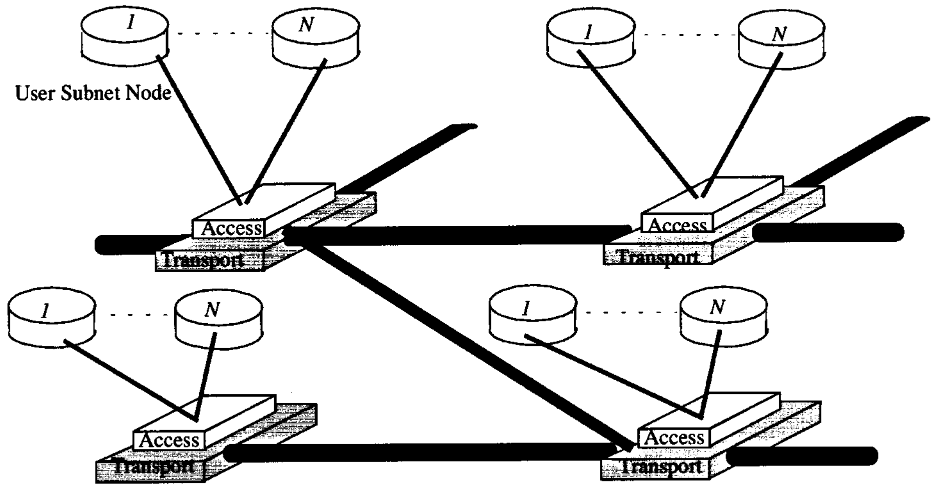


Fig. 14. Upgraded transport layer function.

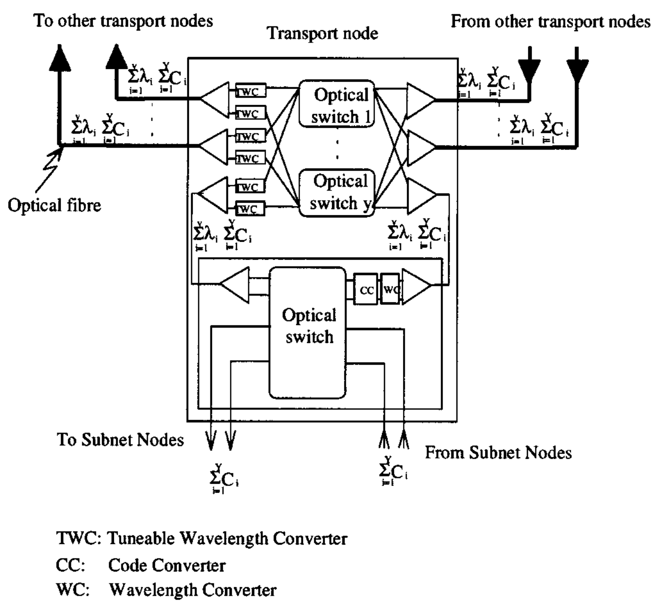


Fig. 15. A schematic architecture of the transport node with add–drop capability.

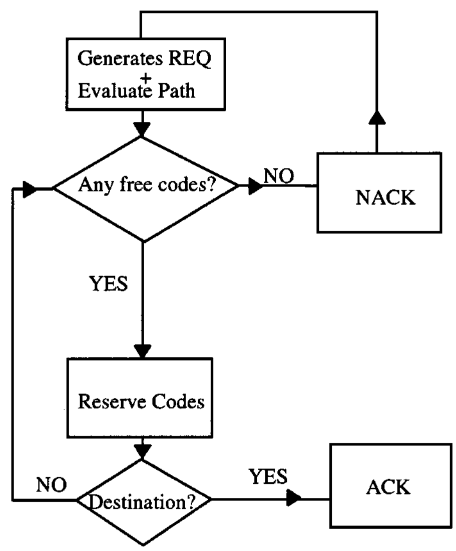


Fig. 16. Code assignment protocol.

transport node will then search for wavelength channels that are not carrying any of the codes reserved by the REQ. Once found the REQ is forwarded to the subsequent intermediate node. If not, a NACK message will be sent back to the user subnet node and all the reserved codes are released. This process is repeated at each intermediate node until the REQ reaches the transport node connecting the destination user subnet node. Each time a wavelength channel that is not carrying the wanted codes is identified, the codes within the channel are reserved. The destination transport nodes then send an ACK message back to the source user subnet node. Each time the ACK arrives at an intermediate node it causes the node to update its routing table and configure its switch connection. Once the user subnet receives the ACK message, it starts releasing the traffic onto the defined code channels into the transport network. A block diagram describing the reservation algorithm is shown in Fig. 15.

The advantage of the second network architecture and the protocols is that it requires less wavelength channels as traffic can hop to any wavelength channel occupied by other connections. However, the codes used within the wavelength channel must not be the same as the codes assigned to the traffic.

E. Network Performance

Simulations were carried out on the network example shown in Fig. 10. Two different network connections were compared. In the first network connection, each transport node is physically connected to an access node and a number of other transport nodes, referred to as NET1. Each access node serves as a gateway to four different traffic sources or users. Each fiber within the optical layer carries four wavelength channels. In the OCDMA/WDMA network each wavelength channel can be multiplexed onto four different codes. The second network connection, NET2, is similar to NET1 except it has two different access nodes connected to each transport node.

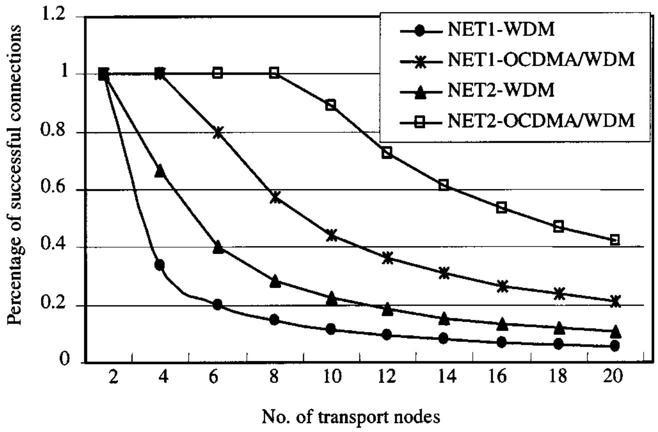


Fig. 17. Network throughput at maximum load condition comparing OCDMA/WDMA strategy and WDMA strategy.

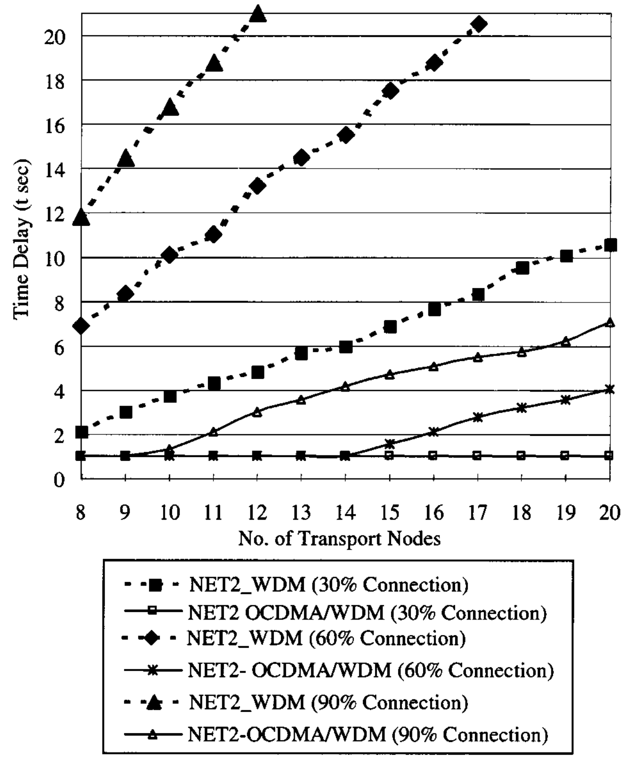


Fig. 18. Average delay at access node comparing OCDMA/WDMA strategy and WDMA strategy.

Two different types of multiplexing strategies were considered; a hybrid OCDMA/WDMA and pure WDMA. Their performance was analyzed by congesting the network. Each network user node generates a load at maximum capacity equivalent to a single wavelength channel bandwidth. The worst case condition was considered whereby all nodes tried to establish connection with a common destination simultaneously. The results shown in Fig. 17 indicate that a network employing OCDMA/WDMA is capable of establishing more connections than a network using WDM only. These results also suggest that OCDMA/WDMA reduces connection setup failure under any network condition and hence, reduces connection set-up time. This is verified by another set of simulations on NET2 which measure the delay experienced by traffic from one user destination wishing to be routed to a particular user destination under two different network conditions. The first considers the case whereby only 30% of the user subnet nodes within the network are busy communicating with that user destination, the second considers the case whereby 90% of the user subnet nodes is communicating with that user destination. It is assumed that whenever a connection is successfully established, the user will hold on to the connection for an average of $10t$ s. From the simulations it was found that each user in an OCDMA/WDMA network encounters less delays at the access node to establish a connection than with pure WDMA (Fig. 18).

F. Advantages of OCDMA/WDMA Networks

The hybrid OCDMA/WDMA networks preserve the advantages of both CDMA and WDMA, offering a series of attributes summarized as follows.

- A multiplexing hierarchy utilising two degrees of freedom, wavelength and code, defining a larger number optical paths than available with pure WDMA.
- The OCDMA dimension allows access to a larger number of addresses, able to support variable bit rate services as well as bursty traffic. Alternatively a fewer number of wavelengths would be required to support a certain level of traffic.
- The OCDMA technique within the WDMA subbands can effectively reduce the transmission limitations imposed by component nonlinearities i.e. effectively "spreading" the limitations introduced by high peak power pulses.
- Fully asynchronous operation providing a flexible access technique.
- Accurate time of arrival measurement offering a means to achieve fine time synchronization.
- Offering a natural increase in the transmission security, not exhibited by any other multiplexing technique.
- Since the high throughput can be obtained by multiplexing many low bit rate OCDMA users, the network has high capacity but low implementation complexity. This implementation allows processing to be carried out at the lower bit-rate, rather than at the chip rate. Hence, conventional electronic processing using existing chip sets can support the network.
- Large transmission capacity, harnessing the huge inherent optical spectrum bandwidth through narrow optical pulses.
- Network expansion can be realized through increasing the number of subnets.

V. Conclusion

A single-mode optical fiber has a total low loss bandwidth of 25 000 GHz. In the future, WDMA will not be the sole multiplexing strategy to fully exploit this bandwidth for high-capacity optical networking. As the available wavelengths resource in mainstream WDMA systems becomes exhausted and given the bit rate limitation within a single wavelength bandwidth has to be overcome, another multiplexing layer has to be used. OTDMA is an obvious approach to achieving this goal, increasing the bit rate carried by each wavelength. Here, another approach has been considered; coherent OCDMA techniques using coherent reception in tandem with WDMA are proposed. The implementation of these OCDMA techniques was introduced and possible optical network architectures based on OCDMA/WDMA were postulated. A comparison between OTDMA and OCDMA, both based on short-pulse laser source, is given in which implementation issues are central to the arguments.

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