Add/drop multiplexing and TDM signal transmission in an optical CDMA ring network

Biao Chen,* Changjian Guo, Jiajia Chen, Linjian Zhang, Qiong Jiang, and Sailing He

Centre for Optical and Electromagnetic Research, Joint Laboratory of Optical Communications, Zhejiang University, Hangzhou 310058, China
Corresponding author: biaochen@coer.zju.edu.cn

Received March 21, 2007; revised May 24, 2007; accepted May 25, 2007; published July 9, 2007 (Doc. ID 81213)

It is shown that a ring topology is better than a star topology for an optical-code-division multiple access (OCDMA) network as an optical metropolitan or local area network in terms of security and capacity. Each node in an OCDMA ring network requires an OCDMA add/drop multiplexer. We present what we believe to be a novel OCDMA add/drop multiplexer that can simultaneously add and drop multiple code channels, and a proof-of-feasibility experiment is demonstrated. An OCDMA ring may also adapt code channels for time domain multiplexing and other digital signal transmission systems. An experiment for the synchronized digital hierarchy (SDH) signal over a OCDMA link is demonstrated. © 2007 Optical Society of America

OCIS codes: 060.4230, 060.4250, 060.4510.

1. Introduction

Code division multiple access (CDMA) has been successfully used in cellular and satellite communications, and has been chosen for mobile communications systems. It offers multiple access capability by allocating a unique code to each user. Over the past two decades, much research work has been done in the establishment of optical computer interconnection and optical digital transmission systems using CDMA techniques [1–5]. Optical implementation of CDMA can utilize the vast bandwidth of optical fiber channels and thus easily satisfy the bandwidth requirements of the spread spectrum transmission, which is the basis of a CDMA technique.

Transmission security and multiple access capability are the main advantages for optical CDMA (OCDMA) networks.

While an OCDMA network usually assumes a star topology, much research work on ring topology has also been carried out in recent years [6,7]. In an optical computer network of OCDMA, N computer stations are interconnected by a star network with a passive $N \times N$ coupler in the center (see Fig. 1). Each station has an OCDMA encoder and an OCDMA decoder, forming a communication node. If data streams are sent by all stations simultaneously, N codes need to be multiplexed along the downstream links of the network because of the broadcast working mode.

In the ring network shown in Fig. 2, each computer is connected to an add/drop multiplexer (ADM) which is the local communication node. A single fiber can be used in the ring for normal operation, whereas a double-fiber ring provides some protection against a fiber cut or failure of one node. For simplicity, we assume that all computers perform point-to-point communications and each station is involved only in one communication pair at a time and sends data to its mate. Then only a maximum number of $N/2$ codes are required on the ring of N nodes, because each destination node removes the corresponding code from the ring so that a pair of nodes can use the same code along the path clockwise or anticlockwise. In other words, the capacity, i.e., the maximum number of stations that can be accommodated, is doubled as compared with the star network for a fixed total number of codes. Furthermore, in a ring network, there are often a combination of multiple codes on the ring and only one scrambling code is needed in order to eliminate the case that only one code is transmitted along the ring, which was proved to be vulnerable to eavesdropping [8]. In a star network, N upstream fibers, which connect the nodes to the coupler, transmit N codes, thus N scrambling codes are needed in order to enhance security. Furthermore, ring fiber networks have been deployed widely for metropolitan area networks and the backbone of

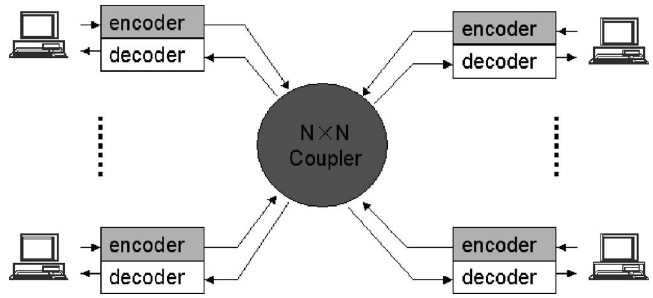

Fig. 1. OCDMA star network.

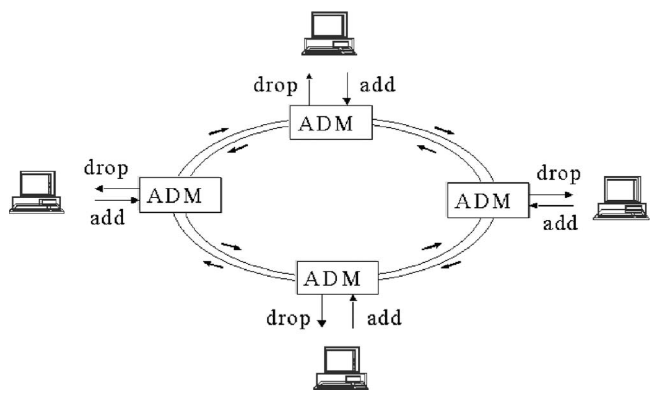

Fig. 2. OCDMA ring network.

access networks. In this paper, we study the key element (i.e., optical add/drop multiplexer) of optical CDMA ring networks and demonstrate a proof-of-feasibility experiment. An OCDMA ring may also adapt code channels for time domain multiplexing and other digital signal transmission systems. We demonstrate an experiment for SDH signal over an OCDMA link.

2. Optical CDMA Add/Drop Multiplexer

An OCDMA star network uses a pair of encoders/decoders at each node, whereas an OCDMA ring network needs to use an add/drop multiplexer at each node. An electronic ADM is the network element for adding and dropping traffic channels in a telecommunication network (especially a ring network). For example, a synchronous digital hierarchy (SDH) ADM may add and drop some groups of telephone traffic from a backbone; a wavelength-division-multiplexing (WDM) ADM adds and drops some light paths of certain wavelengths from a WDM network. Similarly, an OCDMA-ADM adds and drops optical code channels carrying data with the same or different bit rates. Adding a code to the ring can be done just by using a simple passive combiner, but dropping a code from the ring cannot be achieved just by using a simple passive tap because this will cause code circulation and accumulation of noise. The drop units proposed in [6] can remove the dropped code energy from the ring, and thus avoid code circulation and noise accumulation. However, that scheme aims at dropping one code per unit. Our scheme supports flexible multidropping capability, which gives better flexibility for networking applications.

Based on arrayed waveguide gratings (AWGs) and the multicoding approach, we propose in the present paper a new scheme (as shown in Fig. 3) that can drop multiple codes. The encoder and decoder within an add/drop multiplexer can simultaneously encode and decode a set of two-dimensional wavelength-time OCDMA codes. In Fig. 3, the passive splitter on the left side is used to distribute the line signal into different inputs of the decoder. A set of two-dimensional prime and optical orthogonal codes (prime/OOC codes) [9] are used in the encoder and decoder. Each code can be dropped and removed from the ring or forwarded by controlling the 1×2 switch in the forwarding path from the decoder to the encoder. As visualized in Fig. 3, the output signal of a bit period from the decoder consists of the decoded signal peak pulse (also called the autocorrelation peak) accompanied by lower interfering pulses, which are cross-

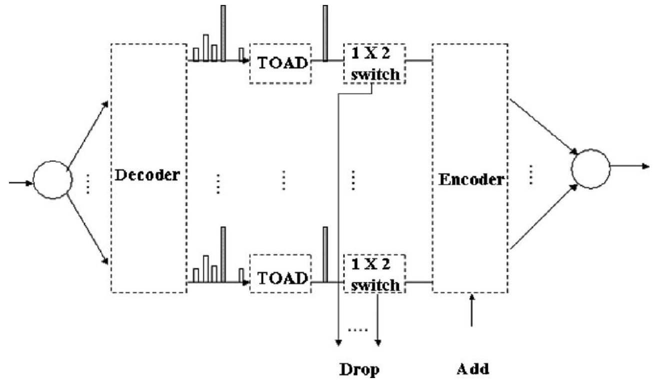

Fig. 3. Structure of the novel add/drop multiplexer.

correlation peaks. The terahertz optical asymmetric demultiplexer (TOAD) [10] in Fig. 3 is used to suppress these interfering pulses effectively. The passive combiner on the right side is used to combine all the re-encoded signals together and outputs the aggregate of encoded light signals.

The encoder and decoder are key parts in this OCDMA-ADM scheme. Figure 4 shows an example of the encoder [with a set of prime (P=3)/(9,3,1) -OOC codes] using a 9×9 AWG as the key component. Binary data is modulated on lightwave by on–off keying (OOK) and in pulse format, i.e., a light pulse during a bit period indicates 1, and none during a bit period indicates 0. The spectrum of the light covers a flat range from λ_1 to λ_9. At the encoder, the light pulse from each data channel is sent into each port on the right side of the AWG through a circulator. For the light pulse input to P_1, the spectrum of the light is sliced into nine chips: λ_1 to λ_9, where each spectrum chip has a width narrower than 0.8 nm. The input pulse is thus divided into nine pulses, which go out from the corresponding ports on the left side of the AWG. Three of the divided light pulses with wavelengths λ_1, λ_2, and λ_4 go through different delay lines and are reflected back by the fiber loop mirrors at the ends, while the other six divided light pulses on the same side of the AWG are in the transmission mode (i.e., nothing is reflected back). Pulses with wavelengths λ_1, λ_2, and λ_4 have undergone delays of 0, 2.5, and 3.5 time-chips, respectively. These three reflected pulses with different wavelengths go back along the same paths as they came into the AWG, and then go through the circulator into the combiner as code λ_1 0000 λ_2 0 λ_4 0 (since the total delays of λ_1, λ_2, and λ_4 are 0, 5 and 7 time-chips, respectively). Similarly, for the light pulse input to P_2, the spectrum of the light is sliced into nine chips, λ_1 to λ_9, and the input pulse is divided into nine pulses going out from the ports on the left side of the AWG. Three of the divided light pulses with the set of wavelengths (λ_2, λ_3, and λ_5) go through different delay lines and are reflected back by the fiber loop mirrors at the ends, while the other six on the same side of the AWG are in the transmission mode. Pulses with wavelengths λ_1, λ_2, and λ_4 have undergone delays of 0, 2.5, and 3.5 time-chips. These three reflected pulses with different wavelengths go back along the same paths as they came into the AWG, and then go through the circulator into the combiner as code λ_2 0000 λ_3 0 λ_5 0, because the total delays of λ_2, λ_3, and λ_5 are 0, 5, and 7 time-chips. According to the cyclic property of AWGs, the code generated from P_{i+1} port of the encoding AWG is λ_{i+1} 0000 λ_{i+2} 0 λ_{i+4} 0 ($i=0,\ldots,8$ mod 9).

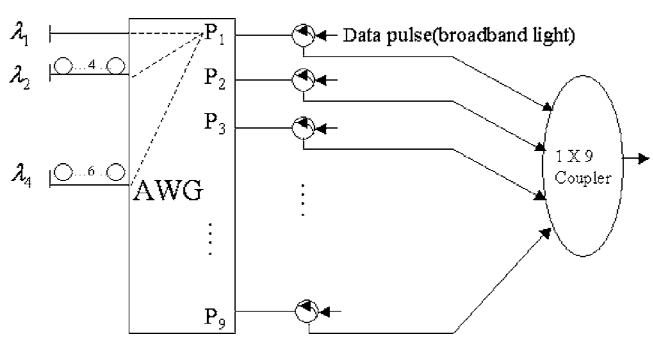

Fig. 4. Structure of our encoder which can encode nine codes simultaneously.

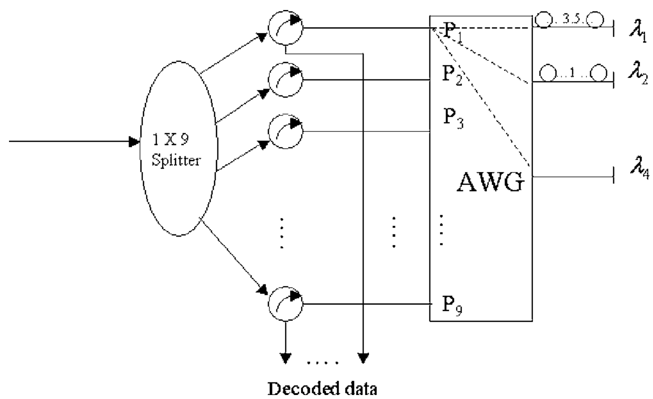

Fig. 5. Structure of our decoder which can decode nine codes simultaneously.

Figure 5 shows the structure of the corresponding decoder, which is the conjugate structure of the encoder. The incoming signal, which is usually the aggregate of encoded light signals coming from the output of the encoder, is distributed to ports P_1 to P_9 by the splitter. This aggregate is the combination of pulse sequences of the different aggregate input to P_1 that includes a light code of λ_1 0000 λ_2 0 λ_4 0, because the delays are matched, i.e., pulses with wavelengths λ_1, λ_2, and λ_4 that are delayed by 0, 5, and 7 time-chips at the encoder are now delayed by 7, 5, and 0 so that pulses overlap with each other. Apart from autocorrelation peaks, P_1 outputs lower cross-correlation peaks originated from unmatched codes in the aggregate. Similarly, at P_{i+1}, one can get an autocorrelation peak reflected back when the aggregate input to P_{i+1} includes a light code of λ_{i+1} 0000 λ_{i+2} 0 λ_{i+4} 0 ($i=0,\ldots,8 \bmod 9$). In this way the proposed decoder can simultaneously decode the incoming matched codes through different ports of the AWG. Similar encoder and decoder structures have been found in [11], but the encoder and decoder described here employ the prime/OOC coding scheme [9], which notably owns larger cardinality and then is more scalable than the Reed-Solomon coding scheme employed in [11].

We made a pair of encoders/decoders and tested them with two different codes. Figure 6 shows the measured transient waves of the combination of two encoded signals and the decoded data for one. The three vertical lines (due to the three wavelengths) in the picture indicate the theoretical peak positions when the input pulse is narrow enough. Because all codes have the same time spreading style, theoretically they have the same transient wave format. The measured transient wave of the combined codes appearing as a blurred shadow in the left shows that the delays are not exact. However, this blurred shadow can be decoded successfully by the decoder as shown in the right part of Fig. 6. In fact, the add/drop multiplexer works well when using arbitrary delay lines in the encoder/decoder instead of those made according to the rule of the prime coding for the time dimension. Especially, the coding scheme becomes one dimensional if no delay lines are used, however, the ruled time spreading style makes it possible to expand the capacity of simultaneous coding by putting together a group of encoders and decoders in parallel with the same kinds of AWGs but with different delay lines.

In a WDM network, a transparent wavelength band, e.g., 20 nm for coarse WDM, can be used to carry OCDMA codes, i.e., OCDMA-over-WDM. In an OCDMA-over-WDM ring network, the group of codes in the same wavelength band can be dropped

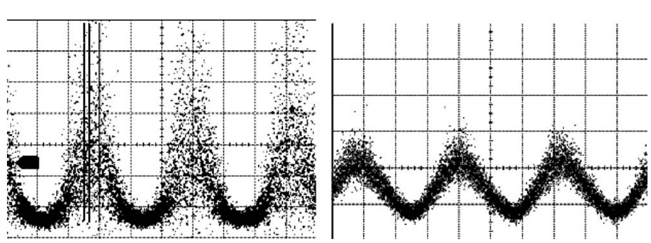

Fig. 6. Measured transient waves of a combination of two encoded signals (left) and the decoded data for a code (right).

simultaneously by using a wavelength drop approach instead of a code drop, but such an approach is not as flexible as the one discussed above.

3. Time Division Multiplexing Over OCDMA

In an access network of OCDMA, N nodes at the user side are connected to the node at the carrier side by a star network with a passive $1 \times N$ coupler in the middle. An end user can use a full bandwidth of a code channel, but in a more economic and efficient way, a number of users share a code channel. Normally the bandwidth sharing is realized with the technique of time division multiplexing (TDM). TDM traffic can be carried out in an OCDMA ring, too. SDH rings can be constructed over codes in an OCDMA ring. SDH transmission systems have been deployed globally in modern telecommunication transport networks as well as access backbone networks for delivering legacy telephone and data services.

A passive optical network (PON) is a system that brings optical fiber cabling and signals almost all the way to the end user, and is a point-to-point optical access network without active elements in the signal path from sources to destinations. All transmissions are performed in an optical line terminal (OLT) at the central office (CO) and many optical network units (ONUs) at the end users.

At a node, different codes can be used for different TDM applications. Figure 7 illustrates an example of TDM access network over an OCDMA ring for a kind of broadband integrated service delivery. The integrated services here mean that multimedia services involving voice, video, and broadband data communication or broadcast are available. In Fig. 7, an OCDMA ring provides logical *Ring* and *Star* networks for SDH (using one code) and PON (using two codes), respectively. Three different OCDMA codes are used in this case. One code is used for constructing the SDH ring owing to the code reuse. SDH add/drop multiplexers are used for adding and dropping circuit-switched narrow band traffic from and to the end users.

TDM over OCDMA needs some interfacing equipment. We have set up an experimental demonstration for SDH over OCDMA, using self-made interfacing equipment. A diagram of the system setup and the eye diagrams of the output digital signal are shown in Fig. 8. The optical signal rate of the SDH terminal is 155 Mbit/s (OC-3). An OC-3 signal receiver and an OCDMA encoder are combined to form the interfacing unit at the transmitting side and an OCDMA decoder and an OC-3 signal transmitter are combined to form the interfacing unit at the receiving side. It can be seen that the eye of the output signal opens clearly. In fact, we can get the error-free digital signal transmission over the system. The SDH over OCDMA approach helps to upgrade from legacy services to integrated services.

For PON, which delivers broadband Internet access, the removing drops are used at the OLT and the nearby RN (remote net, usually a passive coupler connected to ONUs farther away). The other ONU node should not remove or drop the code from the OLT, because this code is broadcasted to all ONUs. The illustrated networking functions of TDM-over-OCDMA are just like TDM-over-WDM. The codes act like the wavelengths in a WDM system. An OCDMA system can provide us with better security and scalability.

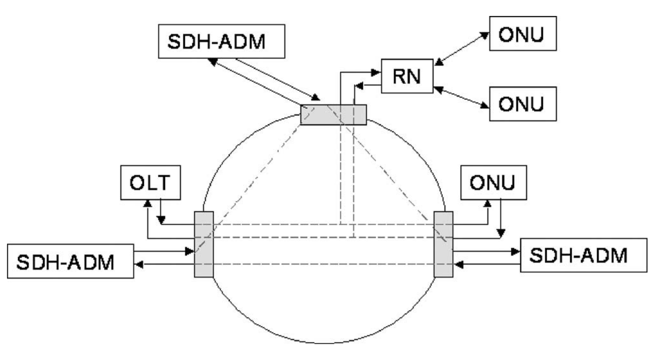

Fig. 7. An example solution for TDM access over an OCDMA ring.

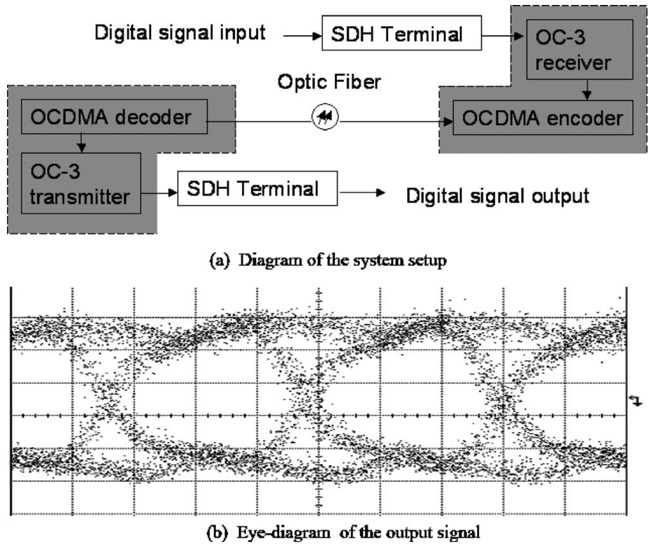

Fig. 8. An experimental demonstration for SDH over OCDMA. (a) Diagram of the system setup; (b) eye diagram of the output signal.

4. Conclusion

For each node, a multiplexer is needed in a ring topology network. We have presented a novel OCDMA add/drop multiplexer for adding and dropping multiple code channels. The feasibility of the multiplexer has been verified with an experiment. With a narrower light pulse source available, we expect to make more experiments in the near future. OCDMA rings are good solutions for upgrading from legacy telephone networks to broadband integrated service networks. An experiment for SDH-over-OCDMA has been demonstrated.

This work was financially supported by the Natural Science Foundation of Zhejiang Province under Rencai Grant R104154.

References

1. P. R. Prucnal, M. A. Santoro, and T. R. Fan, “Spread spectrum fiberoptic local area network using optical processing,” J. Lightwave Technol. **LT-4**, 547–554 (1986).
2. T. Pfeiffer, J. Kissing, J.-P. Elbers, B. Deppisch, M. Witte, H. Schmuck, and E. Voges, “Coarse WDM/CDM/TDM concept for optical packet transmission in metropolitan and access networks supporting 400 channnels at 2.5 Gb/s peak rate,” J. Lightwave Technol. **18**, 1928–1938 (2000).
3. A. Stok and E. H. Sargent, “The role of optical CDMA in access networks,” IEEE Commun. Mag. **40**, 83–87 (2002).
4. K.-I. Kitayama, N. Wada, and H. Sotobayashi, “Architectural considerations for photonic IP router based upon optical code correlation,” J. Lightwave Technol. (Special Issue on Optical Networks) **18**, 1834–1844 (2000).
5. A. J. Mendez, R. M. Gagliardi, H. X. C. Feng, J. P. Heritage, and J.-M. Morookian, “Strategies for realizing optical CDMA for dense, high speed, long span, optical network applications,” J. Lightwave Technol. **18**, 1685–1696 (2000).
6. Camille-Sophie Brès, Ivan Glesk, Robert J. Runser, and Paul R. Prucnal, “All-optical OCDMA code-drop unit for transparent ring networks,” IEEE Photon. Technol. Lett. **17**, 1088–1090 (2005).
7. J.-S. Wu and C.-L. Lin, “Fiber-optic code division add-drop multiplexers,” J. Lightwave Technol. **18**, 819–824 (2000).
8. T. H. Shake, “Security performance of optical CDMA against eavesdropping,” J. Lightwave Technol. **23**, 655–670 (2005).
9. S. P. Wan and Y. Hu, “Two-dimensional optical CDMA differential system with Prime/OOC codes,” IEEE Photon. Technol. Lett. **13**, 1373–1375 (2001).
10. J. P. Sokoloff, P. R. Prucnal, I. Glesk, and M. Kane, “A terahertz optical asymmetric demultiplexer (TOAD),” IEEE Photon. Technol. Lett. **5**, 787–790 (1993).
11. S. Kim, “Cyclic optical encoders/decoders for compact optical CDMA networks,” IEEE Photon. Technol. Lett. **12**, 428–430 (2000).