Study on Optical CDMA*

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Abstract: The current OCDMA research areas and some optical CDMA schemes were reviewed. The spectral phase encoded time spreading (SPECTS) OCDMA technique, which exhibits a good prospect for practical applications in future broadband access networks, was introduced, and some limitations that may affect the implementation of OCDMA systems were investigated. The project of developing actual OCDMA system was proposed and analyzed. The results show that multiple access interference (MAI) and confidentiality are the main barriers as an enabling technology of optical LAN in the near future.

Key words: Optical fiber communications; Optical CDMA; Multiple access interference

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0 Introduction

Multiple-access techniques are required to meet the demand for high-speed, large-capacity communications in optical networks which allow multiple users to share the fiber bandwidth. There are three major multiple access approaches: time-division multiple access (TDMA), wavelength-division multiple access (WDMA) and optical code division multiple access (OCDMA).

Code division multiple access (CDMA) technique, which has been developed into a great success in wireless communication, enables multiple access communications by assigning unique codes to users. This concept was introduced into fiber optic communication systems in the middle of 80's as optical CDMA (OCDMA), where encoding and decoding operations are all performed in optical domain.

Recently, OCDMA is receiving increasing attention due to its potential for multi-user reconfigurable local area networks (LANs). Especially when considering fine granularity of traffic in local-area-networks.

Of the OCDMA research areas, three major areas are extensively investigated and demonstrated in many ways. The first major area is to create novel hardware technology for optical encoding and decoding that enables OCDMA systems operating with the underlying bit rate exceeding 10 Gb/s and supporting a large number of simultaneous and potential users. The second is to investigate and demonstrate novel coding algorithms that maximize the number of simultaneous users of an OCDMA network with an acceptable BER ($< 10^{-9}$). The third is to develop innovative concepts in advanced OCDMA network architectures and high system security, to evaluate quantitatively the benefits resulting from the use of OCDMA in networks for specific applications.

Although many different OCDMA schemes have been proposed and demonstrated in recent years [1-2], these can't reduce people's doubt: can OCDMA be used in real network? How far can OCDMA approaches go in high speed optical access networks to replace or coexist with other optical technologies? This paper will examine this issue from system performances. In this paper, we focused our interest on OCDMA system and provided a review of research progress about optical CDMA schemes, and then examined their challenges in OCDMA system realization. Finally, security issues which can effectively advance the application are also discussed.

1 Research progress of some optical CDMA schemes

Today, a number of different OCDMA schemes have been proposed and demonstrated, which can be classified by two criteria. The first is by working principle. In incoherent OCDMA, the coding is performed on optical power basis, therefore, the Optical codes are handled in unipolar (0,1) manner. In coherent OCDMA, the coding is performed on field amplitude basis that the Optical codes are handled in the bipolar (−1, +1) manner all optically. Another is by processing dimensions. The coding can be 1-Dimensional (1-D) performed in either time domain or frequency domain, or be

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2-dimensional (2-D) performed in frequency and time domains simultaneously.

Schemes based on incoherent processing (summing of optical powers) and 1-D time domain coding are generally the easiest to implement, but offer relatively poor performance, and have a little available coding space.

To increase the available coding space, time-wavelength (two-dimensional, or 2-D) coding schemes have been proposed, where each code chip corresponds to a specific time position and wavelength position within a bit as determined by a code matrix [3-5]. This scheme may utilize either coherent or incoherent sources but employs incoherent processing (summing of optical powers from chips with different wavelength and time positions). Fig. 1 is an incoherent, asynchronous wavelength-hopping time-spreading 2-D OCDMA system.

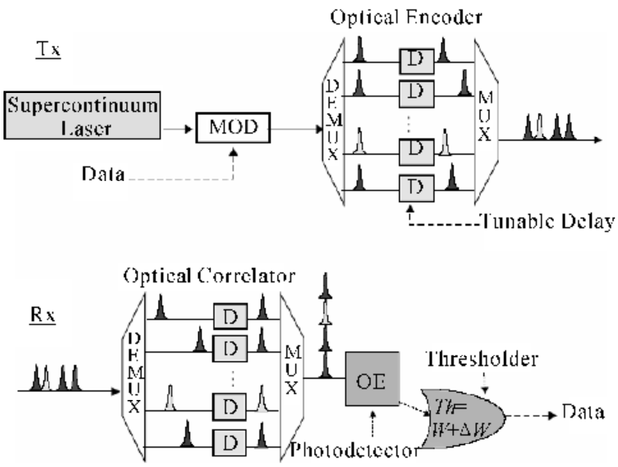

Fig. 1 Wavelength-hopping time-spreading 2-D OCDMA system

It works as follow. In the transmitter, a supercontinuum laser modulated via on-off keying is passed through an encoder. The encoder slices the supercontinuum into multiple wavelengths, aligns each pulsed wavelength to its appropriate timeslot using adjustable delay lines, and then recombines the wavelengths with a WDM multiplexer for transmission into the network. After distribution and transmission through the network, the encoded signals arrive at the decoders of users' receivers, The arriving signal passed through an optical correlator that is similar to the encoder, except that the wavelength and the time-delay arrangements are reversed. A photodiode converts the intensity of the signal at the output of the correlator to an electrical signal which is threshold-detected to recover the data bits.

However , as in radio spread - spectrum systems , a critical limitation of OCDMA networks is the multiple access interference (MAI). As different users whose signals may be overlapped both in time and frequency share a common communications medium; multiple access is achieved by assigning different, minimally interfering code sequences to different code-division multiple-access (CDMA) transmitters, which must subsequently be detected in the presence of multiple access interference (MAI) from other users.

Coherent processing based on manipulation of optical fields, which can be made to sum to zero, is needed for strongest suppression of MAI and for best performance. So recently, coherent OCDMA using ultra-short optical pulse is receiving increasing attention with the progress of reliable and compact encoder/decoder devices, such as spatial light phase modulator (SLPM), planar lightwave circuit (PLC) and superstructured fiber Bragg grating (SSFBG). Among these coherent OCDMA schemes, we will be in favor of the spectral phase encoded time spreading (SPECTS) OCDMA technique which exhibits a good prospect for practical applications in future broadband access networks [1-6]. In a SPECTS OCDMA network, each user encodes their broadcast with a unique phase code that is part of an orthogonal (or quasi-orthogonal) set. Encoding causes the pulses to spread in time, and recovery of the pulse (decoding) can only occur if the correct conjugate phase code is applied. The code orthogonality causes all other decoded broadcasts to remain temporally spread as multi-access interference (MAI), and these may be separated from the recovered pulse using optical processing, such as synchronous time gating and/or nonlinear thresholding. This year ,an error-free, 32 users at 10 Gb/s each, for a 320-Gb/s capacity optical code division multiple access (OCDMA) network testbed employing the spectral phase encoded time spreading (SPECTS) technique has been demonstrated [7].

Very short optical pulses containing many phase locked optical frequencies are spread in time according to a phase code. This was effective, but the short pulses cover a huge amount of bandwidth, so this is not compatible with normal WDM, and the number of codes is limited, so the use of bandwidth is not efficient. A improved scheme is to find a way to be compatible with WDM, and also use the bandwidth efficiently.

And also in this year, a cost-effective WDM/DPSK-OCDMA sharing a single multi-port encoder in central office, tunable decoders in ONU has been successfully demonstrated with frequency efficiency of 0.27 bit/s/Hz in truly-asynchronous environment. The total capacity is 3-WDM × 10-OCDMA × 10.71Gbps, and transmission distance is 111 km in field trial, without FEC and optical thresholding [8].

2 Challenges in OCDMA systems development

A critical issue of OCDMA networks is the multiple access interference (MAI) noise and signal-interference (SI) beat noise [1,9-12]. In a common multi-user OCDMA network, multiple access interference (MAI) noise is the main issue. The MAI could be suppressed effectively by employing a time gate . Using of time gating technique could improve the BER performance by eliminating the MAI noises outside the gating window, however, strict synchronization (chip level) is needed that makes it not suitable in asynchronous OCDMA. Recently, multi-user coherent OCDMA experiments have been demonstrated by utilizing optical thresholding based on second harmonic generation (SHG) in periodically-poled lithium niobate (PPLN) and nonlinear effect in high nonlinear fiber (HNLF) to significantly suppress the MAI noise. However, coherent OCDMA could suffer from severe signal-interference (SI) beat noise if the signal and interferences overlap each other. The SI beat noise, which dominates over the MAI noise in such system, eventually limits the maximum number of active users that can be supported in the network. Unfortunately, the SI beat noise could not be suppressed effectively by optical thresholding as it accompanies with the recovered signal pulse. Therefore, either slot-level or chip-level timing coordination has been applied to enable multi-user transmission. Slot-level coordination is a rough synchronous approach that the signal and interferences are intentionally separated in time, therefore no beat noise will arise. Chip-level coordination is a precise synchronous approach that the signal and each interference have to be precisely aligned on a chip-level with zero interference to mitigate the beat noise. Both of them are synchronous approaches that sacrifice the most desired characteristic of OCDMA: "asynchronism". Besides, the former one significantly lowers the frequency efficiency of the system, while the latter one requires very strict network synchronization (~ ps) that is almost impossible in practical.

For practical OCDMA network application, the capability of asynchronous multi-user access is essential. One of the effective approaches is employing ultra-long optical code (OC) with uniform cross-correlations to lower the MAI. Phase-shifted SSFBG en/decoder is one desired candidate that has the capability to process OC as long as 511-chip with chip-rate as high as 640 Gchip/s enabling us to challenge a truly-asynchronous OCDMA. In theory, about 7 active users can be supported for error free transmission at 1.25 Gbit/s with data-rate detection, while by employing optical thresholding to reject the MAI, the number of users could be doubled. But the scheme often require long code lengths (511 chips or greater) to achieve adequate performance, which are difficult to implement at multi-gigabit rates, or are unable to demonstrate high capacity. So full asynchronism is difficult to implement in practice while simultaneously maintaining sufficient MAI suppression with enough simultaneous users (potentially scalable to >100).

Optical thresholder is also a crucial device to perform chip rate MAI noise elimination without synchronization. The optical thresholding techniques that have been proposed for OCDMA application include: using intensity dependent nonlinear frequency shift in DSF, holly fiber, or high nonlinear fiber (HNLF), nonlinear optical loop mirror (NORM), and periodically-poled lithium niobate (PPLN) waveguide. For practical OCDMA application, the most desired technique should have a high contrast ratio with low operating power. This still is a challenge for current techniques.

In fact, there is still no multiple-user OCDMA network experiment in a strict sense, as all of them used the same data source and with specific time delays between different users. Particularly, in the multiple users experiments with coherent OCDMA schemes, the signals from different users were intended to be separated to avoid overlap each other. Therefore, the impairment of MAI and beat noises, which in theory are the dominant noises in the system , haven't been experimentally investigated so far.

Another critical issues of O-CDMA networks is the security issues in OCDMA [13-14]. While enhanced security has often been cited as a potential benefit of OCDMA technology, the degree of this enhancement has not been thoroughly investigated by now. Because of optical hardware limitations and the code orthogonality required for low multiple access interferences, feasible spectral-phase-encoding solutions are limited to several well-known code families that contain relatively small number of codes. As a result, the confidentiality protection offered by such choices of optical-codes is relatively weak; an eavesdropper can use brute-force searching in the known sets to easily determine the applied code. So how to achieve high confidentiality for code-limited spectral-phase-encoded OCDMA, or other OCDMA schemes, it is still a big problem if the security features of OCDMA are of interest, and it will be extremely valuable to military platform networks and free-space optical communication systems, such as inter-satellite communications.

3 Conclusions

In this paper, we discussed the current state of OCDMA technology, the challenges faced in developing OCDMA system. We don't know whether OCDMA will be used in real networks in near future. May be only time will tell. But we believe the technology of all-optical OCDMA encoding and decoding can find other applications such as optical packet switch and optical signal processing.

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光CDMA系统研究

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摘 要:评述了目前光CDMA系统的研究领域和一些最新的实现方案,对基于SPECTS的光CDMA技术方案进行了分析,研究了影响光CDMA系统实现的主要因素,对方案实际实现中面临的技术难点进行了讨论,提出了多址干扰和安全性是近期OCDMA应用可行性的主要技术障碍.

关键词:光纤通信;光CDMA;多址干扰

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