Upstream OCDMA-TDM Passive Optical Network Using a Novel Sourceless ONU

Mohammad Gharaei, Catherine Lepers, and Philippe Gallion

Abstract—**OCDMA over conventional TDM PON leads to increase access network capacity by multiplexing TDM signals with OCDMA codes. We propose a novel sourceless ONU for OCDMA-TDM PON within a centralized light source placed at OLT. Sparser and longer extended quadratic congruence (EQC) codes with good correlation properties are used as optical CDMA en/decoders. However, multiple access interference (MAI) can limit the number of simultaneous users in this system. We analyze BER performance of sourceless OCDMA-TDM PON using four different EQC codes. Finally, network scalability and throughput performance of the proposed scheme are analyzed. These analyses over OCDMA-TDM PON show an upgrade of bandwidth and network capacity with an advantage of sourceless ONUs compared to the conventional TDM PON.**

Index Terms—**Access network; optical code-division multiple access (OCDMA); passive optical network (PON); reflective ONUs.**

I. INTRODUCTION

With explosive growth of Internet based traffic in recent years such as high-definition television (HDTV), file sharing, online gaming, and social networking, the network operators require high-speed and large capacity access networks. Passive optical network (PON) has been largely accepted as an attractive solution for the last-mile bottleneck, providing broadband access networks to end users [1]. PON is a point to multipoint optical network, typically a star topology, connecting an optical line terminal (OLT) on the service provider side to the multiple optical network units (ONUs) on the subscriber side via a passive star coupler (SC). Time division multiplexing (TDM) PON is an emerging low-cost technology which has been widely accepted and deployed in the recent years. In TDM PON, the total bandwidth of the system is shared by several users with the benefit of low installation and maintenance cost [2]. To avoid collision in uplink transmission of TDM PON, OLT allocates an appropriate time slot to each ONU and during each time slot an ONU can forward its data toward OLT. Generally, OLT and ONUs exchange control messages (REPORT and GATE messages) in order to grant a time slot to the ONU, which clarifying the start and duration of upstream transmission by an ONU. The control messages follow multi-point control protocol (MPCP) which is defined by the IEEE 802.3ah task force [3].

The next generation PON needs to supply new services providing a graceful bandwidth upgrade from the current-generation PON. PON upgradability is carried out not only for increasing the bandwidth but also for increasing the number of end users and also distances coverage. Hereafter, we discuss a new approach for the next generation PON by means of upgrading the current TDM PON in order to increase the bandwidth and user capacity. TDM PON does not exploit the huge bandwidth of optical fiber. On the other hand, the huge bandwidth provided by wavelength division multiplexing (WDM) PON is too expensive for access network users. Among different multiplexing scenarios to increase network capacity without scarifying the bandwidth, a great deal of attention has paid to optical code division multiple access (OCDMA) technique [4]. OCDMA technique can provide all-optical processing, potential information security, protocol transparency, asynchronous access and simplified network control for access networks [5],[6]. This technique permits multiple users access to the transmission media by assigning different optical codewords to users. A code or sequence of pulses referred to as “chips” is attributed to each user to encode its data bits. The encoded data are then broadcasted into the network and are only recognized by the matched decoder. However, when the number of simultaneous users increases, the multiple access interference (MAI) effect becomes significant [7]. This is due to the superimposition of different encoded users data within a chip time duration at detection stage. The upgrade of conventional TDM PON with the OCDMA technique results in an access network with increased capacity and also enhanced security issue [8],[9].

Recently, centralized light source issue has been largely paid attention as a potential superiority for the next generation access networks. To reduce the cost of PON by eliminating ONU's laser source for upstream transmission, the reflective ONU is a convenient solution [10],[11]. A centralized light source is placed at OLT to supply optical carrier for uplink transmission. The ONU upstream functionality is to modulate user data on the carrier and send it back to the OLT. Furthermore, identical reflective ONU leads to avoid maintenance and installation difficulties for service providers. Upon to the system architecture, different reflective ONU can be employed, for example reflective SOA or injection-locked Fabry Perot (IL-FP) laser [12],[13].

OCDMA systems are categorized into coherent versus incoherent systems based on used optical sources. Incoherent OCDMA systems use broadband light sources such as light emitting diode (LED), and broadband erbium-based source or FP laser source [14]. It takes an advantage of low cost TXs, however, they suffer mainly from low modulation speed and ASE noise. On the other hand,

M. Gharaei and C. Lepers are with Télécom SudParis, CNRS SAMOVAR, 9 Rue Charles Fourier, 91011 Evry Cedex, France (phone: +33-160-764-019; e-mail: mohammad.gharaei@it-sudparis.eu).

P. Gallion is with Télécom ParisTech, CNRS LTCI, Ecole Nationale Supérieure des Télécommunications, 46 rue Barrault, 75634 Paris, France.

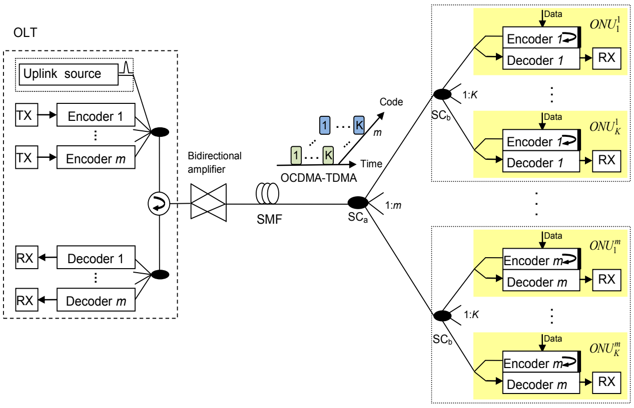

Fig. 1. Network architecture of OCDMA-TDM PON.

coherent OCDMA systems use mostly mode locked laser diode (MLLD) which can increase the modulation speed, even though it adds to the system's cost and complexity [15]. Hence, the sourceless issue in coherent OCDMA system is more profitable approach. Recently, different sourceless ONUs for coherent OCDMA systems have been proposed [16],[17]. In this paper, we propose a new simple reflective ONU for OCDMA-TDM PON. In this architecture the upstream carrier is generated at OLT and then transmitted toward ONUs. It is modulated by user data at ONUs, encoded and finally reflected back to the OLT. The encoding and reflection process in our system is carried out by superstructured fiber Bragg grating (S-FBG) based encoder. We simulate the OCDMA-TDM PON system using the code with convenient correlation properties. Afterwards, the bit error rate (BER) performance of uplink transmission is simulated considering the MAI effect. The estimation on power budget will then define the scalability of this network. Finally, the throughput performance of this architecture is analyzed.

The rest of this paper is organized as follows. In section II, we present the system architecture of upstream transmission using reflective ONUs in OCDMA-TDM PON. In section III, the simulation model is described and we test the BER performance of this system with reflective ONU architecture. In section IV, network scalability and throughput performance are analyzed. Finally, we conclude this paper in the fifth section.

II. OCDMA-TDM PON PRINCIPLES

Fig.1 shows the architecture of OCDMA-TDM PON using reflective ONUs. This architecture is an upgrade of TDM-PON with taking the advantage of higher user capacity and bandwidth. In OCDMA-TDM PON, each ONU is upgraded with a pair of en/decoder to encode upstream signal or decode the downstream signal. In this architecture, each optical code is reused by the number of users based on TDM approach. By taking m as a code capacity and K as a number of timeslots for the upstream transmission, $m \times K$ is the number of set up ONUs. In the downstream transmission, the data destinated to the ONU_j^i (i-th codeword and j-th timeslot) is well decoded by decoder$_i$. In the upstream transmission, first the uplink carrier pulse is generated at OLT and then transmitted towards ONUs. It is modulated with ONU's data, then coded, and reflected back to the OLT. Since the coding process is carried out in reflection based encoder, the encoded upstream signal is simply sent back to OLT. We note that, the upstream signals are transmitted at different wavelength compared to downstream signal transmission. Finally, the ONU_j^i data is well-decoded by i-th decoder at OLT. It is pointed out that the uplink transmission is the most critical issue since it suffers from the attenuation twice. That's why a bidirectional amplifier is used in this scheme.

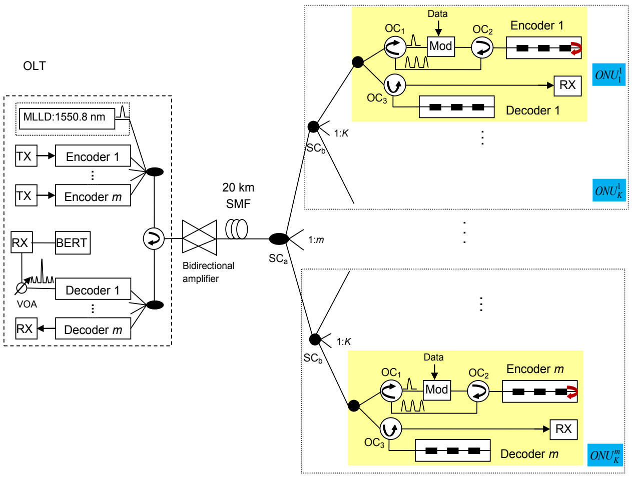

Fig. 2. Simulation setup for OCDMA-TDM PON with new reflective ONUs.

ONUs with different codes can communicate with OLT using an asynchronous OCDMA technique, without needing a new collision avoiding protocol. Here, we apply direct sequence OCDMA (DS-OCDMA) technique in which each user data bit is encoded with a given sequence of pulses in temporal axes [18]. DS-OCDMA is a convenient technique in the case of OCDMA-TDM PON application, since the coding process is done in temporal dimension and can be simply integrated with TDM. As a result, different ONUs within a same time slot can simultaneously communicate with OLT without collision. At the detection stage in OLT or ONUs, the non-destinated signals cannot be decoded since the decoders cannot build a well autocorrelation function. The autocorrelation function is considered as the sum of the different optical power of all pulses to be combined within one chip time duration. On the contrary, the crosscorrelation function results in multiple access interference (MAI) noise. It originates from the improper decoding of an optical signal which is incident on an optical receiver. The superimposition of different encoded user data within a chip time duration at detection stage, produce this effect.

The performance of OCDMA system is strongly limited by MAI effect. As the number of simultaneously users increases in OCDMA system, BER performance degrades. MAI increases proportionally with the number of users transmitting data across the network. In this architecture, there are *m-1* users' signals which interfere with the desired signal.

III. SIMULATION AND RESULTS

Fig. 2 shows the simulation setup for sourceless OCDMA-TDM PON. A mode-locked laser diode (MLLD)

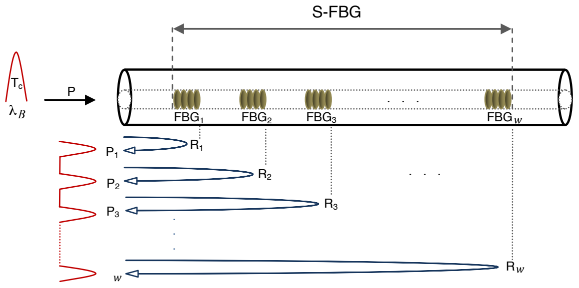

Fig. 3. Schematic of S-FBG encoder (P: mean optical intensity).

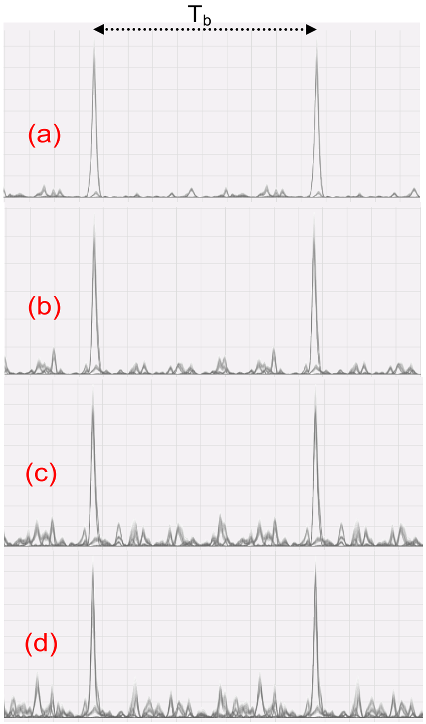

Fig. 4. Autocorrelation functions of EQC codes with 4 codewords when (a) one user (b) 2 users (c) 3 users (d) 4 users is/are active.

at 1550.8 nm wavelength is used at OLT as an uplink light source with the repetition rate of 10 GHz. The return to zero (RZ) pulse train of full width at half maximum (FWHM) of 50 ps is then amplified and sent to all ONUs. The ONUs with the given time slot, can modulate on this impulse carrier. The impulse carrier at the second port of the optical circulator$_1$ (OC$_1$) is passed to the third port of the OC$_1$ to modulate with ONU data. The 50 ps pulse train is RZ modulated by an electro-optic modulator at 625 Mb/s data bit rate per user (with a pulse ratio of 1:16). Then it is passed through the second port of the OC$_2$ into the Encoder$_i$. The modulated pulse of 50 ps enters the S-FBG (Fig. 3) with the following parameters: P denotes the mean optical intensity, T_c denotes the time duration (50 ps), and λ_B denotes the Bragg frequency. This pulse is reflected by FBG$_1$,…,FBG$_\omega$ with the reflectivity of $R_1,\ldots,R_\omega$, where ω represents the code weight, respectively. However, the reflectivity of the first FBG should not be too high in order to permit the pulse to pass through it and arrive to the next FBG. The reflected pulses create the encoded data. Since the encoding process is done in reflection, the modulated signal is encoded and reflected to the third port of the OC$_2$. Finally, ONU upstream signals are transmitted to OLT from the second port of the OC$_1$. The code function in reflection is the key to build this reflective ONU. Moreover, by employing reflective ONUs in OCDMA-TDM PON, the beating interference due to the same optical sources in ONUs is reduced.

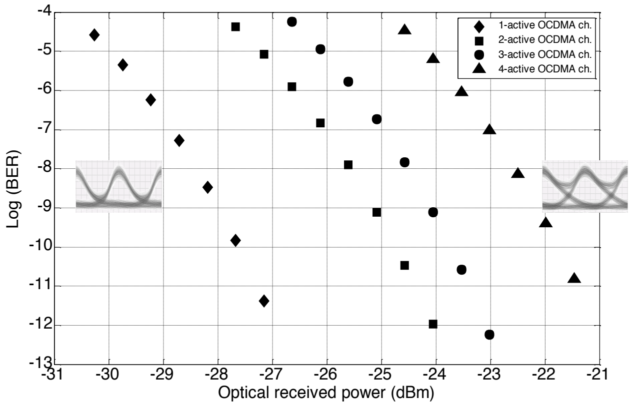

Fig. 5. BER performance of upstream OCDMA-TDM PON

To cope with the optical distribution network (ODN) losses, a bidirectional amplifier is used to boost the upstream reflected signal. The encoded upstream data is routed toward the OLT by passing from the amplifier with a saturation power of 15 dBm. At the detection stage, the encoded data are passed through the decoder to construct the autocorrelation function. The decoded signal consists of the autocorrelation peak and MAI noise from other users which degrade BER performance. The autocorrelation function is detected by a photodetector at OCDMA transmission bit rate.

BER performance of DS-OCDMA systems is highly dependent on the code family characteristics. The sparser and longer extended quadratic congruence (EQC) codes with non-periodic structure demonstrate a higher autocorrelation and lower crosscorrelation properties [19]. Therefore, these codes are used to have an OCDMA system less sensitive to interferometric perturbations. Codewords are implemented by using superstructured fiber Bragg gratings (S-FBG) reflecting a 50 ps user pulse train. It is pointed out that we generate an on-off keying (OOK) codeword. Each “1” bit of user-data is reflected by FBGs, and an optical fiber length (ΔL) between two successive FBGs represents the number of “0” chips. In order to simulate DS-OCDMA physical layer close to the experiment, the spectra of encoders/decoders in [19], are imported into our simulation environment. The performance of transmission system is carried out by using VPItransmissionMaker software.

Fig. 4 shows the autocorrelation functions of EQC codes with the capacity of four codes after decoder$_1$ in OLT. We observe the increase level of side lobes by increasing the number of active OCDMA channels. This highlights the effect of MAI.

Fig. 5 shows BER performance of OCDMA-TDM PON using EQC codes with capacity of 4 channels. The electrical waveforms of the received signal with one and four active channels are shown in this figure. We have successfully achieved a BER=10^{-9} with 4-simultaneously active channels in OCDMA-TDM PON with a received power of -22 dBm.

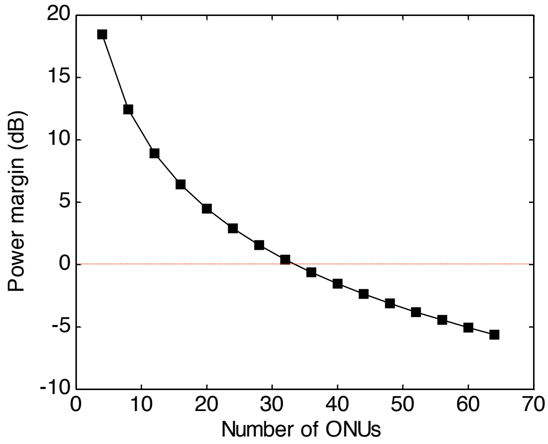

Fig. 6. Power margin of OCDMA-TDM PON.

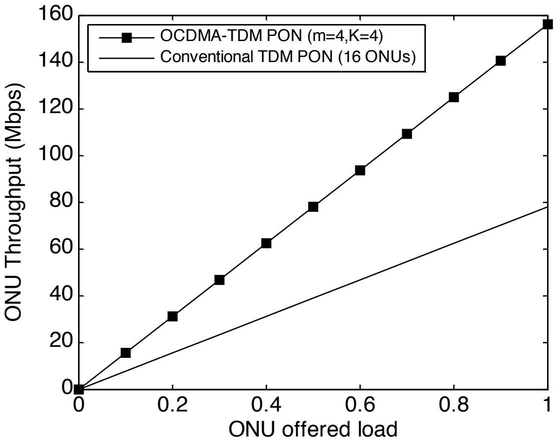

Fig. 7. Throughput performance of OCDMA-TDM PON.

The power penalty between 1-active channel and 4-simultanous active channels in the system is around 5 dB. The degradation of BER performance by adding the ONUs using different code word is due to MAI. However, this system with 4-simultaneously channels cannot achieve a BER=10^{-12} due to interferometric perturbations. It is noted that, when a high number of PNs are active in the network, optical thresholder can be used to eliminate MAI in order to reach to the better BER performance [20].

IV. NETWORK ANALYSES

A. *Network Scalability*

Optical power budget (PB) should be high enough to cover ODN losses. Here we analyze the network architecture by means of power budget and network scalability. In this architecture, ODN losses are due to fiber, circulators and splitter losses. To evaluate the optical PB, we consider commercial device losses. Table I, summarizes the optical losses and power management for OCDMA-TDM PON, where m and K are the splitting ratio related to the code capacity and the number of timeslot, respectively. Since upstream signals experience two times the ODN losses, a bidirectional amplifier is primordial in this architecture. The receiver sensitivity, RX_{sen}, is defined as the minimum optical power required yielding a bit error rate of 10^{-9}. In this Table, power margin is defined as the difference between received optical power and minimum optical power required by the receiver to achieve the standard BER performance.

Fig. 6 shows the network scalability of OCDMA-TDM PON for our simulation when m=4. As the number of ONUs is increased, ODN losses are also increased which will limits power budget. OCDMA-TDM PON can achieve 32 ONUs with a power margin of 0.5 dB. However, a system with more than 32 ONUs in this PON does not have adequate power margin for data transmission which requires more power budget.

TABLE I
POWER MARGIN CALCULATION FOR UPSTREAM TRANSMISSION USING THE SIMULATION PARAMETERS

PARAMETER	VALUE
Coupler loss (SC_a)	10 log (m) dB ×2
Coupler loss (SC_b)	10 log (K) dB ×2
Laser optical power	0 dBm
Fiber loss	0.2 dB/km ×2
Circulator loss	1.5 dB
Coupler 1×2	3 dB ×2
Amplifier nominal output power	15 dBm
Insertion loss ($IL_{OCDMA\text{-}TDM\ PON}$)	21.5+20 log (m×K) dB
Power Margin	$30\text{-}RX_{sen}\text{-}IL_{OCDMA\text{-}TDM\ PON}$ dB

B. *Network Throughput*

A TDM PON system with 16 ONUs and data rate of 1.25 Gb/s results in 78.12 Mb/s data bit rate per ONU. Here we use a static bandwidth allocation just to address the advantage of OCDMA-TDM PON, however dynamic bandwidth allocation (DBA) could be employed to increase the resource efficiency [21]. In our simulation model with the same number of ONUs and m=4, the default data bit rate of 625 Mb/s is reused by K=4 timeslots. Fig. 7 compares ONU throughput performance of the proposed OCDMA-TDM PON with the conventional TDM PON. The OCDMA-TDM PON throughput is given by $1/(T_c.L.K)$, where T_c is the chip time duration in a code sequence and L is the OCDMA code length. The EQC code length is $L=p^2$, where p is the prime number. If we consider four ONUs per OCDMA channel, EQC codes with $p=5$ must be chosen since the multiplexing capacity is equal to $p-1$. The result shows that, OCDMA-TDM PON throughput can be about two times of the conventional TDM PON. We can also interpret the increase of bandwidth as an increase in number of ONUs if only the PB permits. It means that we can have 32 ONUs in OCDMA-TDM PON with the data bit rate of 78.12 Mb/s.

The number of ONUs can be increased by bringing into play a higher multiplexing capacity codes. However, the code capacity in DS-OCDMA system depends on the code length. Therefore, the OCDMA-TDM PON throughput is a compromise between the number of ONUs and the OCDMA code length. Finally, the result shows the improved throughput and capacity performance of proposed OCDMA-TDM PON compared to conventional TDM PON.

V. CONCLUSION

OCDMA-TDM PON results in an upgrade of bandwidth, and network capacity of TDM-PON. In OCDMA-TDM PON, each OCDMA channel is reused by TDM channel to increase the number of ONUs. As a result multiple asynchronous OCDMA channels can communicate simultaneously with OLT. We have proposed a new reflective ONU for OCDMA-TDM PON to eliminate the uplink source in ONUs. OCDMA-TDM PON benefits from the reflection-based coding of S-FBG encoders to redirect the upstream signals toward OLT. We have demonstrated BER performance of 10^{-9} for 4-simultaneously active channels in OCDMA-TDM PON using sourceless ONUs. Finally, the throughput analysis demonstrates the improved throughput of OCDMA-TDM PON compared to conventional TDM PON.

REFERENCES

[1] R. Lin, "Next generation PON in emerging networks," in proc. OFC/NFOEC 2008, paper OWH1.

[2] L. G. Kazovsky, W. T. Shaw, D. Gutierrez, N. Cheng, S. W. Wong, "Next-generation optical access networks," J. Lightw. Technol., vol. 25, no. 11, Nov. 2007, pp. 3428-3442.

[3] IEEE 802.3ah: Ethernet in the first mile task force, June 2004.

[4] J. A. Salehi, "Code division multiple access techniques in optical fiber networks-Part I: Fundamental principles," IEEE Trans. Commun., vol. 37, no. 8, pp. 824–833, Aug. 1989.

[5] A. Stok, E. H. Sargent, "The role of optical CDMA in access networks," IEEE Commun. Magazine, vol. 40, no. 9, pp. 83-87, Sep. 2002.

[6] G. Cincotti, N. Wada, K. I. Kitayama, "Secure OCDM-based PON," In proc. optical fiber communications (OFC/NFOEC09), San Diego, CA, paper: OThI6, 2009.

[7] S. Shen, A. M. Weiner, G. D. Sucha, and M. L. Stock, "Bit error rate performance of ultrashort-pulse optical CDMA detection under multi-access interferences," Electron. Lett., vol. 36, no. 21 , pp. 1795-1797, Oct. 2000.

[8] T. H. Shake, "Security performance of optical CDMA against eavesdropping," J. Lightw. Technol., vol. 23, no. 2, pp. 655-670, Feb. 2005.

[9] N. Nakagawa, *et al.*, "Scalable GE-PON over OCDMA without sacrifice of upstream bandwidth: Principle and its experimental demonstration of 2xGE-PON systems over 2×63-chip code," in proc. ECOC08, Sept. 2008.

[10] J. I. Kani, M. Teshima, K. Akimoto, N. Takachio, H. Suzuki, K. Iwatsuki, "Optical access network for wide-area gigabit access services," IEEE Commun. Mag., vol. 41, no. 2, pp. S43-S48, Feb. 2003.

[11] S. H. Yam, J. Kim, D. Gutierrez, F. Achten, "Optical access network using centrallized light source, single-mode fiber + broad wavelength window multimode fiber," J. Opt. Netw. vol. 5, no. 8, pp. 604-610, Aug. 2006.

[12] F. Payoux, P. Chanclou, M. Moignard, R. Bernot, "Gigabit optical access using WDM PON based on spectrum slicing and reflective SOA," in proc. ECOC05, paper We3.3.5, 2005.

[13] S. J. shin *et al.*, "Low-cost WDM-PON with colorless bidirectional transcievers," J. Lightw. Technol. vol. 24, no. 1, pp. 158-165, Jan. 2006.

[14] Z. El-Sahn, B. J. Shastri, M. Zeng, N. Kheder, D. V. Plant, and L. A. Rusch, "Experimental demonstration of a SAC-OCDMA PON dith burst-mode reception: local versus centralized sources," J. Lightw. Technol., vol. 26, no. 10, pp. 1192-1203, 2008.

[15] S. Ayotte and L. A. Rusch, "Experimental comparison of coherent versus incoherent sources in a four-user λ-t OCDMA system at 1.25 Gb/s," Photonics Technology Letters, vol. 17, no. 11, pp. 2493-2495, Nov. 2005.

[16] G. Cincotti, N. Kataoka, N. Wada, X. Wang, T. Miyazaki and K. I. Kitayama "Demonstration of asynchronous, 10Gbps OCDMA PON system with colorless and Sourceless ONUs," in proc. ECOC09, 2009.

[17] S. Yoshima, *et al*. "Demonstration of burst transmission of multiple capacity 10G-PON over OCDMA uplink using hybrid SSFBG encoder/multi-Port decoder and 10 Gbps burst-mode receiver," In proc. OFC/NFOEC, paper: PDPD4, 2009.

[18] I. Fsaifes, C. Lepers, M. Lourdiane, P. Gallion, V. Beugin and P. Guignard, "Source Coherence Impairments in a Direct Detection DS-OCDMA system," Applied Optics, vol. 46, no. 4, pp. 456-462, Feb. 2007.

[19] I. Fsaifes, C. Lepers, R. Gabet, M. Douay, and P. Gallion, "Performance analysis of quadratic congruence codes using superstructured fiber Bragg gratings for a flexible data rate coherent DS-OCDMA system," J. Opt. Netw. vol. 7, no. 7, pp. 692-703, Jul. 2008.

[20] X. Wang, N. Wada, K. Kitayama, "Performance degradation in coherent OCDMA due to receiver's bandwidth limit and improvement by using optical thresholding," in proc. LEOS, pp. 638-639, Oct. 2005.

[21] K. Fouli, T. Berisa, and M. Maier, "Optical Coding for Enhanced Real-Time Dynamic Bandwidth Allocation in Passive Optical Networks," J. Lightw. Technol., vol. 27, no. 23, pp. 5376-5384, Dec. 2009.