# Hybrid WDMA/OCDM system with the capability of encoding multiple wavelength channels by employing one encoder and one corresponding optical code

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A hybrid wavelength division multiple access (WDMA)/optical code division multiplexing (OCDM) system is proposed, where the optical code is not the same as the address of every optical network unit (ONU); rather, the code is a virtual fiber of hybrid passive optical network (PON). To our knowledge, this is the first report analyzing a single encoder/decoder with a single corresponding optical code being exploited to encode/decode multiple wavelength signals simultaneously. This system enables OCDM to become transparent to ONU so that the existing wavelength division multiplexing (WDM) PON can be upgraded. Thus, redesigning the optical line terminal and ONU can be easily accomplished, and greatly decreasing the number of encoder/decoder becomes possible. In experiment, we only employ two encoder/decoder pairs to combine two WDM-PONs in one fiber. Simulation results confirm the feasibility of the proposed system.

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Wavelength division multiple access (WDMA) is used in the wavelength division multiplexing (WDM) passive optical networks (PONs) for higher bandwidth. Code division multiple access (CDMA) is considered a candidate for the next generation broadband access networks because it has the advantages of asynchronous transmission, secure communication, tell-and-go access protocol, soft capacity on demand, and huge degree of scalability[1]. However, WDM-PON systems accommodate limited optical network units (ONUs), even if the spectral range is 0.8 nm. If every channel carries 10-Gb/s signal, there is still a 90-GHz bandwidth not occupied between two neighboring wavelength channels. Therefore, a method of overlaying optical CDMA (OCDMA) on WDM-PON has been proposed to fill the gaps of the WDM grids. This is a promising solution for high-capacity and high-bandwidth access networks[2,3].

Figure 1 shows the architecture of the hybrid PON, where OCDMA channels are overlaid on the WDM grids. On each WDM grid, $\lambda_m (m = 1, 2, \cdots, M)$, $N$ users can be accommodated by individually assigning each user with a different optical code $\mathrm{OC}_n (n = 1, 2, \cdots, N)$. The same code sequence can be used on all the different wavelength channels. Each optical line terminal (OLT) carried on one wavelength accommodates $N$ channels of signal.

Previous studies conducted on hybrid systems combining OCDMA and WDMA techniques have been implemented based on the OCDMA/WDMA architecture, as shown in Fig. 1[4−13]. These systems have the same mode as that in wireless networks, where every ONU is assigned to an encoder/decoder pair.

In this letter, we propose a hybrid WDMA/optical code division multiplexing (WDMA/OCDM) system, where the optical code is not the same as the address of every ONU, but is a virtual fiber of hybrid PON. The structure of the hybrid WDMA/OCDM system is illustrated. We employ two optical orthogonal codes (OOCs) to combine two WDM-PONs in one fiber experimentally.

The different encoding/decoding techniques in OCDM have almost the same principle of delaying the optical pulse, which makes it possible not to employ switches to control the on/off of pulse sequences. The position of the delay pulse can be considered as a virtual automatic on/off switch. When the optical pulse is triggered, it will be automatically delayed for a specific amount of time. This gives the optical encoder/decoder the ability to process multiple asynchronous channels of signal carried on different wavelengths simultaneously. The new hybrid system takes advantage of such unique features. Its architecture is shown on Fig. 2.

In the WDMA/OCDM system, one en/decoder $(1, 2, \cdots, N)$ with one optical code will encode or decode $M$ channels of signal carried on $M$ different wavelengths

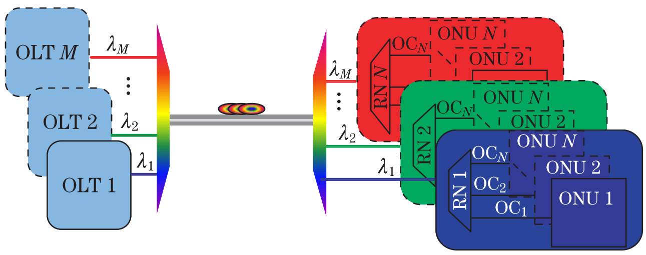



Fig. 1. Architecture of the OCDMA/WDMA system. RN: remote node.

$(\lambda_1, \lambda_2, \cdots, \lambda_M)$ from remote nodes (RNs) simultaneously. Thus, one WDM-PON with $M$ ONUs is assigned to one optical encoder/decoder pair and one corresponding optical code. Only $N$ pairs of en/decoder are needed if the system accommodates $M \times N$ ONUs, and the OCDMA/WDM PON needs $M \times N$ pairs of en/decoder under the same capacity. Another advantage of the proposed system is that it can upgrade the existing WDM-PON to hybrid WDMA/OCDM PON without redesigning the OLT and ONUs.

To illustrate the feasibility of the proposed system, a simulation was set up (Fig. 3). The signals from two WDM-PONs were encoded by two different encoders (encoders 1 and 2) with two OOC codeword blocks (i.e., $(1, 3, 9)$ and $(2, 5, 6)$) of an $(n, \omega, \lambda) = (13, 3, 1)$ OOC[14]. The first WDM-PON accommodated eight ONUs carried on eight center frequencies (192.1, 192.3, 192.5, 192.7, 192.9, 193.1, 193.3, and 193.5 THz). The second WDM-PON had two ONUs carried on two center frequencies (192.9 and 193.1 THz). The transmitter (Trads 1–10) of every ONU consisted of a mode-locked laser diode (with repetition frequency of 10 GHz and pulse duration of 2 ps), an intensity modulator, and a signal generator that generates 10-Gb/s payload data. The temporal intensity pulse sequence of Trad 5 is illustrated in Fig. 4. Tunable fiber delay line was used to control the system for it to remain asynchronous. The encoder/decoder consisted of a coupler, three fixed fiber delay lines, and a splitter. The delay time of every branch in encoder/decoder was a multiple of 7 ps since the periodicity of each chip was assigned to be 7 ps in the OOC codeword blocks.

Signals from Trads 1–10 were transmitted on channels 1–10. All the other channels were activated when one of the ten channels was detected. Eight channels signals from the first WDM-PON were combined by the WDM multiplexer (MUX) first, and then encoded by encoder 1. The second WDM-PON was processed similarly. Signals from two WDM-PONs were then combined and transmitted on 25-km single mode fibers (SMFs). To compensate for the widened ultra-short pulse, dispersion-compensating fiber (DCF) was employed after the SMF.

At the destination, signals were divided into two paths.

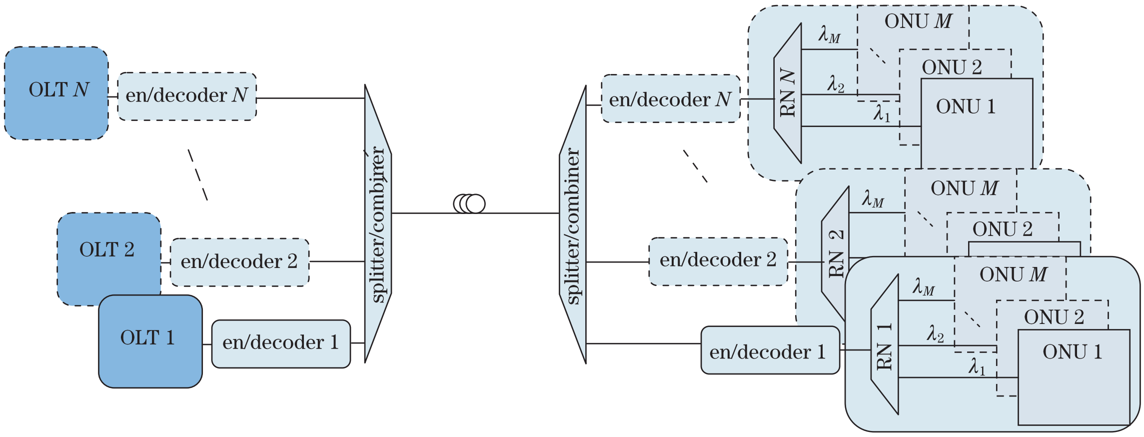



Fig. 2. Architecture of WDMA/OCDM system.

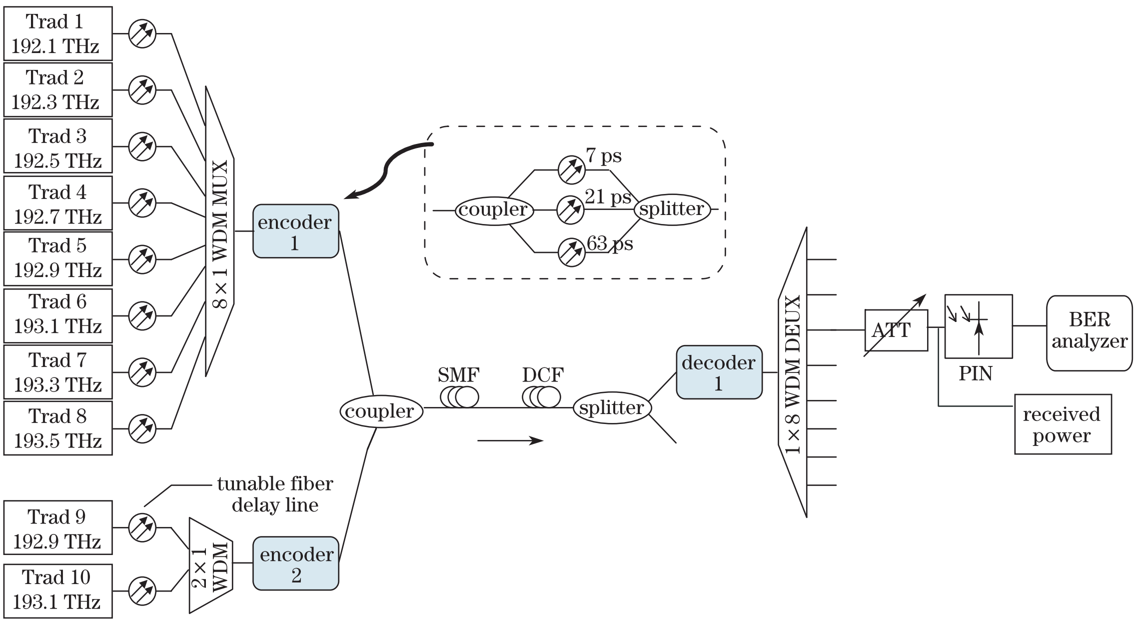



Fig. 3. Simulation setup of WDMA/OCDM system. MUX: multiplexer; DEMUX: demultiplexer; SMF: single-mode fiber; DCF: dispersion-compensating fiber; ATT: attenuator; BER: bit error rate.

Signals of one path were decoded by decoder 1, corresponding to encoder 1, and then were divided into eight channels by WDM demultiplexer (DMUX). The detected signals from Trad 5 are illustrated in Fig. 5. Comparing the pulse to Fig. 4, it was widened from 2 to 3.125 ps because of the sampling rate employed (the dispersion of 25-km SMF has been compensated by the DCF). The auto-correlation side lobe and cross-correlation from channel 9 contaminated the decoded signals; however, the signals can be detected correctly by employing proper threshold. The receiver consisted of an attenuator (ATT), a PIN photodiode, and a bit error rate (BER) analyzer.

Figure 6 shows the back-to-back BER of channels 1–8 with the attendant of interference signals from channels 9 and 10. All the signals can be detected clearly with BER$<10^{-9}$, even if the 8-channel signals from one WDM-PON are simultaneously encoded and decoded with one OOC codeword. This proves that the hybrid WDMA/OCDM system is feasible and can provide perfect performance. The BERs of channels 5 and 6 are slightly bigger than those of other channels because channels 9 and 10 lead the cross-correlation to them and decrease the signal-to-noise ratio. Figure 7 shows the BERs after 25-km transmission. The application of DCF compensates dispersion of 25-km SMF and the nonlinear effects have little influence on the performance.

In conclusion, we have proposed a hybrid system of WDMA/OCDM, in which one optical encoder/decoder with one optical code is exploited to encode/decode multiple channels of signals carried on different wavelengths simultaneously. This model is different from the existing hybrid systems where the optical code is considered as the address of every ONU. We have assigned the optical code to be a virtual fiber of hybrid PON. This enables the system to be upgraded to the present WDM-PON system seamlessly without designing the ONU and the OLT anew. This also decreases the number of en/decoder greatly. Compared with the existing

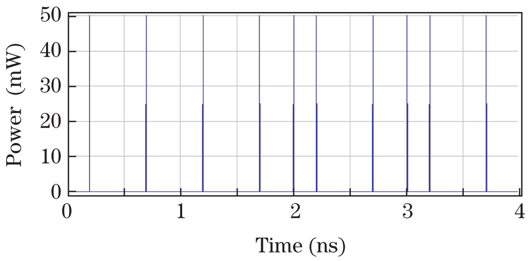



Fig. 4. Time pulse sequences of Trad 5 on channel 5.

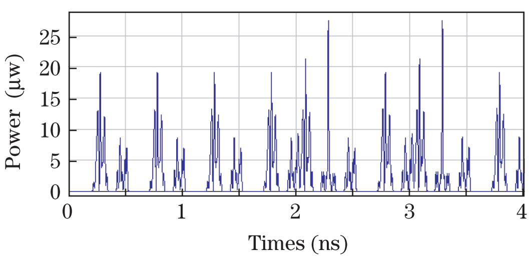
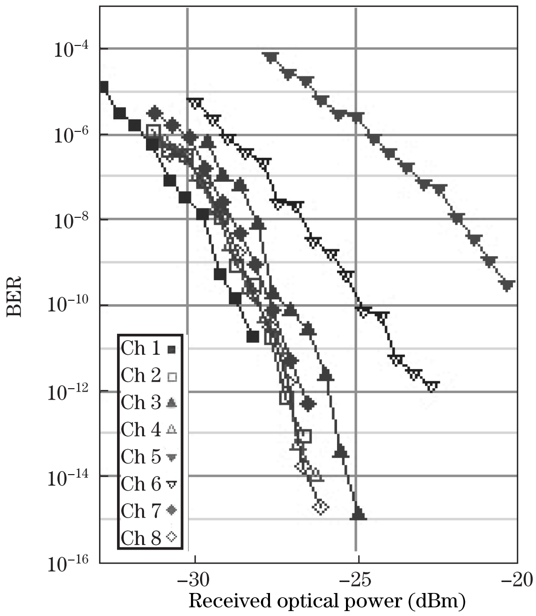



Fig. 5. Time pulse sequence on channel 5 after dividing by WDM DEMUX.



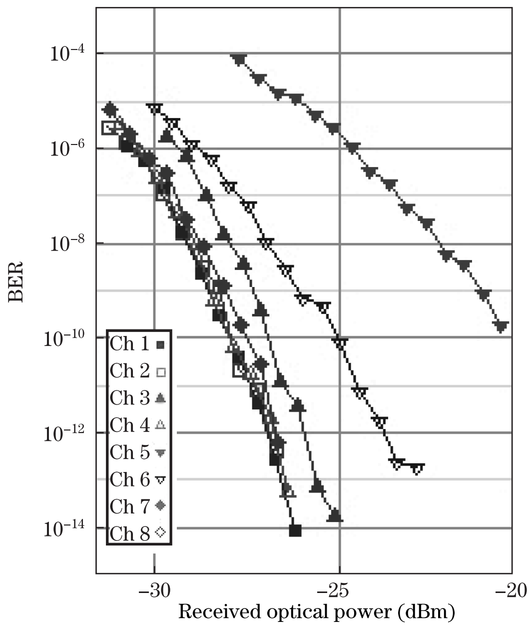




Fig. 7. BER of hybrid system after 25-km transmission.

$M$ WDM$\times N$ OCDM system, the proposed hybrid system decreases the number of encoder/decoder to $N$ from $N \times M$ under the same ONU accommodation. Simulation demonstration has verified that this system works well.

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